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Potential Hazards from Future Volcanic Eruptions in California

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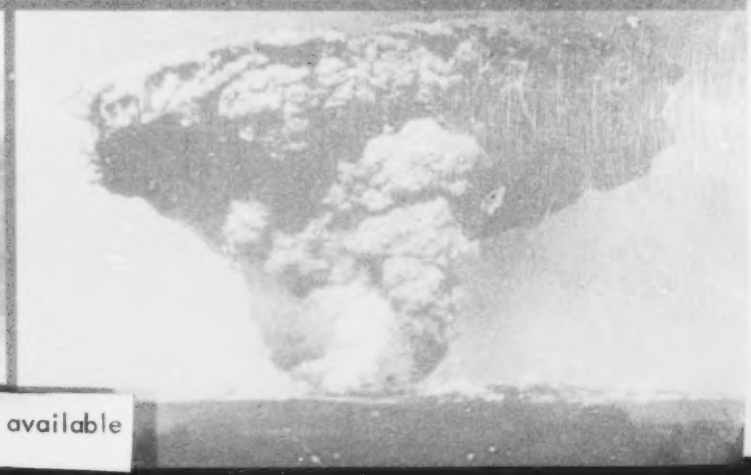

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Cover photographs

Upper left

Aerial view of Cinder Cone, east of Lassen Peak, California. Early travelers in northeastern California described what may have been an eruption of Cinder Cone in A.D. 1851 (Finch, 1937). The most recent documented eruption of Cinder Cone occurred about 400 radiocarbon years ago (Mike Clynne, oral communication, 1989). Photograph by C. Dan Miller.

Upper right

View from the southwest of Mount Shasta and Shastina (left), California. Mount Shasta has erupted frequently during the last several thousand years; the most recent eruption occurred in A.D. 1786 (Finch, 1930). Photograph by Lyn Topinka.

Lower left

Aerial view toward the south of the Mono-Inyo volcanic chain, California. Panum Crater (and dome), right foreground. The most recent eruptive episode of the Mono-Inyo chain occurred from multiple vents about 600 years ago. Photograph by C. Dan Miller.

Lower right

View from Anderson, California, of the May 22, 1915, eruption of Lassen Peak. The ash cloud reached an altitude of more than 25,000 feet. Photograph by B.F. Loomis, courtesy of Department of Interior, National Park Service.

Potential Hazards from Future Volcanic Eruptions in California

By C. DAN MILLER

An assessment of expectable kinds of future eruptions and their possible effects on human lives and property based on the eruptive behavior of volcanoes in California during the last 10,000 years

U.S. GEOLOGICAL SURVEY BULLETIN 1847

DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

U. S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

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UNITS OF MEASURE AND THEIR EQUIVALENTS

To convert metrics	Multiply by	To obtain
Millimeters (mm)	0.03937	Inches (in.)
Centimeters (cm)	.3937	Inches (in.)
Meters (m)	3.28	Feet (ft)
Kilometers (km)	.62 (about ⅜)	Miles (mi)
Cubic meters (m^3)	35.31	Cubic feet (ft^3)
Cubic kilometers (km^3)	.2399 (about ¼)	Cubic miles (mi^3)
Kilometers/hour (km/h)	.62	Miles/hour (mi/h)
Square kilometers (km^2)	.3861	Square miles (mi^2)

GLOSSARY OF SELECTED VOLCANIC TERMS

Andesite: Medium-colored dark gray volcanic rock that contains 53–63 percent silica.

Ash (volcanic): Fragments of lava or rock smaller than 2 mm in size that are blasted into the air by volcanic explosions.

Ashcloud: Cloud of ash formed by volcanic explosions or derived from a pyroclastic flow.

Ashfall (airfall): Ash falling from an eruption column or ashcloud.

Basalt: Dark-colored volcanic rock that contains less than 53-percent silica.

Base surge: Turbulent, low-density cloud of rock debris and water and (or) steam that moves over the ground surface at high speed. Base surges are generated by explosions.

Block: Fragments of lava or rock larger than 64 mm in size that are blasted into the air by volcanic explosions.

Dacite: Volcanic rock that is typically light in color and contains 63–68 percent silica.

Debris avalanche (volcanic): Flowing or sliding, wet, or dry mixture of soil and rock debris that moves away from a volcano at high speed.

Directed blast: A hot, low-density mixture of rock debris, ash, and gases that moves at high speed along the ground surface. Directed blasts are generated by explosions.

Fumarole: An opening in the ground from which hot water vapor and (or) volcanic gases are emitted.

Holocene: Period of geologic time from about 10,000 yr ago until the present.

Lapilli: Fragments of lava or rock between 2 and 64 mm in size that are blasted into the air by volcanic explosions.

Lava dome: A steep-sided mass of viscous lava extruded from a volcanic vent.

Lava flow: Stream of molten rock that erupts relatively nonexplosively from a volcano and moves slowly downslope.

Mafic: Term used to describe volcanic rock or magma composed chiefly of dark-colored, iron- and magnesium-rich minerals.

Magma: Molten rock within the Earth.

Mudflow (debris flow): A flowing mixture of water-saturated debris that moves downslope under the force of gravity.

Phreatic eruption: An explosion of steam, water, mud, and other material. May result from heating of groundwater by magma, and may generate base surges.

Phreatomagmatic eruption: An explosion composed of magmatic gases and steam derived from groundwater or surface water, combined with lava and other debris.

Pyroclastic flow: Mass of hot, dry rock fragments mixed with hot gases. Moves away from a volcano at high speeds.

Pyroclastic surge: Turbulent, low-density cloud of hot rock debris and gases that moves over the ground surface at high speed.

Quaternary: Period of geologic time from about three million years ago until the present.

Rhyolite: Typically a light-colored crystalline or black glassy volcanic rock or magma.

Silicic: Term used to describe silica-rich volcanic rock or magma.

Tephra: Materials of all sizes and types that are erupted from a volcano and deposited from the air.

Potential Hazards from Future Volcanic Eruptions in California

By C. Dan Miller

Abstract

More than 500 volcanic vents have been identified in the State of California. At least 76 of these vents have erupted, some repeatedly, during the last 10,000 yr. Past volcanic activity has ranged in scale and type from small rhyolitic and basaltic eruptions through large catastrophic rhyolitic eruptions. Sooner or later, volcanoes in California will erupt again, and they could have serious impacts on the health and safety of the State's citizens as well as on its economy. This report describes the nature and probable distribution of potentially hazardous volcanic phenomena and their threat to people and property. It includes hazard-zonation maps that show areas relatively likely to be affected by future eruptions in California.

The potentially more hazardous eruptions in the State are those that involve explosive eruption of large volumes of silicic magma. Such eruptions could occur at vents in as many as four areas in California. They could eject pumice high into the atmosphere above the volcano, produce destructive blasts, avalanches, or pyroclastic flows that reach distances of tens of kilometers from a vent, and produce mudflows and floods that reach to distances of hundreds of kilometers. Smaller eruptions produce similar, but less severe and less extensive, phenomena.

Hazards are greatest close to a volcanic vent; the slopes on or near a volcano, and valleys leading away from it, are affected most often and most severely by such eruptions. In general, risk from volcanic phenomena decreases with increasing distance from a vent and, for most flowage processes, with increasing height above valley floors or fan surfaces. Tephra (ash) from explosive eruptions can affect wide areas downwind from a vent. In California, prevailing winds cause the 180-degree sector east of the volcano to be affected most often and most severely. Risk to life from ashfall decreases rapidly with increasing distance from a vent, but thin deposits of ash could disrupt communication, transportation, and utility systems at great distances, and over wide regions, in eastern California and adjacent states.

Volcanic eruptions are certain to occur in California in the future and can be neither prevented nor stopped, but actions can be taken to limit damage from them. Reduction of risk to life and property can be effected by avoiding threatened areas and by taking protective measures to reduce the effects when and where vulnerable areas cannot be avoided. Monitoring of volcanic precursors generally can identify the locality of impending volcanic activity, even though it often does not pinpoint the nature or timing of an eruption, or even its certainty. Hazard-zonation maps can then be used to guide decisions regarding evacuation and other response activities. Thus, effective monitoring of volcanoes in the State, combined with preparation of contingency plans to deal with future eruptions, can help reduce risk to lives and property.

Manuscript approved for publication, February 17, 1988.

INTRODUCTION

More than 75 volcanic vents in California have been active during the last 10,000 yr, and several tens of volcanoes have erupted, some repeatedly, during the past several thousand years. Moreover, more than 10 volcanoes have erupted during the past 600 yr, including Mount Shasta, Lassen Peak and nearby Cinder Cone, volcanoes in the Medicine Lake Highland, and the Mono-Inyo volcanic chain. Although eruptions have occurred relatively infrequently in California during the last few thousand years and few if any might be expected to occur during any one person's lifetime, the potential danger to life and property from volcanoes in California is great enough to be of concern.

Within the State of California, 23 separate volcanic areas and more than 500 volcanic vents have been identified (Jennings, 1975). California volcanoes demonstrate great variety in their types and in their geologic settings; potential volcanic hazards within the State vary accordingly. The tectonic settings of volcanic centers range from subduction-related volcanism in the northern part of the State (Mount Shasta and Lassen Peak), to volcanism related to crustal stretching and thinning along the Sierra Nevada escarpment (Mono-

Inyo volcanoes and Long Valley caldera), to volcanism in an area of active crustal spreading in the Salton trough (Salton Buttes rhyolite domes) (fig. 1). Past eruptions within the State have run the gamut from small basaltic eruptions through catastrophic caldera-forming eruptions of rhyolite such as the one that formed the Bishop Tuff about 700,000 yr ago; virtually every known type of eruptive activity has occurred within California (table 1).

Volcanic activity within the State of California has occurred on the scale of "human time" as well as "geologic time" as evidenced by eruptions at Lassen Peak in 1914–1917 and recent unrest in the Long Valley–Mono Lake area of central-eastern California. Although relatively minor in scale compared to many prehistoric eruptions within the State, the Lassen Peak eruptions included at least two blasts that devastated areas to the east of the peak and produced mudflows that inundated the valley floors of Hat and Lost Creeks. Tephra from the most violent eruption, on May 22, 1915, was carried by prevailing winds as far as about 500 km to the east where it fell in Elko, Nev.

Following four large ($M>6$) earthquakes that occurred in the Long Valley region during May 1980, numerous swarms of relatively shallow earthquakes occurred within the south moat of the caldera near the community of Mammoth Lakes. These earthquake swarms continued from 1980 until late 1983 and were accompanied by uplift and deformation within the caldera that continues at the time of this writing (fall 1987). These events have greatly increased concerns about the possibility of renewed eruptive activity in the Long Valley–Mammoth Lakes area and have resulted in increased monitoring efforts in the region and preparation of emergency response plans by local, State, and Federal officials.

Sooner or later, a volcano in California will erupt again, and the ever-expanding use of areas near volcanoes increases the potential impact of an eruption on the State's economy and on the health and safety of its citizens. The elements at risk from future eruptions in California include its population, power resources including nuclear reactors, water supplies, transportation, communications, agriculture, industry, and recreation. Alfors and others (1973) estimated very conservatively that losses in California due to volcanic eruptions could amount to 50 million dollars between 1970 and the year 2000. The results of the 1980 Mount St. Helens eruptions, however, suggest that far greater losses are likely from even small future eruptions in California. Eruptions of Mount St. Helens in May and June 1980, that were small in volume relative to possible future events in California, resulted in estimated short-term losses to the economy of Washington State of 970 million dollars (MacCready, 1982). Moreover, 60 lives were lost during the May 18 eruption, and additional economic losses are still accumulating at the time of this writing (fall 1987).

The purpose of this report is to describe potential hazards from future eruptions of volcanoes in California. This assessment is based on the locations, types, and scales of past eruptions and the nature, distribution, and hazardous effects of products from those eruptions. By anticipating the nature and extent of potential volcanic hazards and the nature and likelihood of possible warnings, planners and public officials such as the State Office of Emergency Services (OES) and local governments can:

1. make long-range, land-use-planning decisions in areas of recognized hazard, and
2. make hazard-response plans and delineate refuge areas and possible evacuation routes,

thereby mitigating the effects of future eruptions.

CLASSIFICATION OF VOLCANIC VENTS

With the exception of the Clear Lake volcanic field, volcanoes of Quaternary age in California are concentrated primarily in the eastern half of the State in a discontinuous band that extends from the California-Oregon border south to Mexico. In this study, volcanoes that last erupted more than about 100,000 yr ago are not shown on the accompanying maps and have not been considered from the viewpoint of volcanic hazards. If these volcanoes have not erupted during the last 100,000 yr, little likelihood exists that they will erupt again in the next few decades or centuries. Furthermore, for these vents no data exist on eruption characteristics that are recent enough to be useful for forecasting the nature of future eruptive activity. All volcanic vents in California that are known or inferred to be younger than about 100,000 yr are plotted on the hazard maps accompanying this report. The vents are subdivided into two groups according to age, 100,000–10,000 yr (Late Pleistocene), or younger than 10,000 yr (Holocene), and broadly according to eruptive style or composition of erupted products. Subdivision of volcanoes according to age is based primarily on radiometric dating (see Luedke and Smith, 1981, and references cited on each of the accompanying maps); where radiometric dates are not available, I estimated ages of deposits from their morphology and degree of dissection, relative age-dating

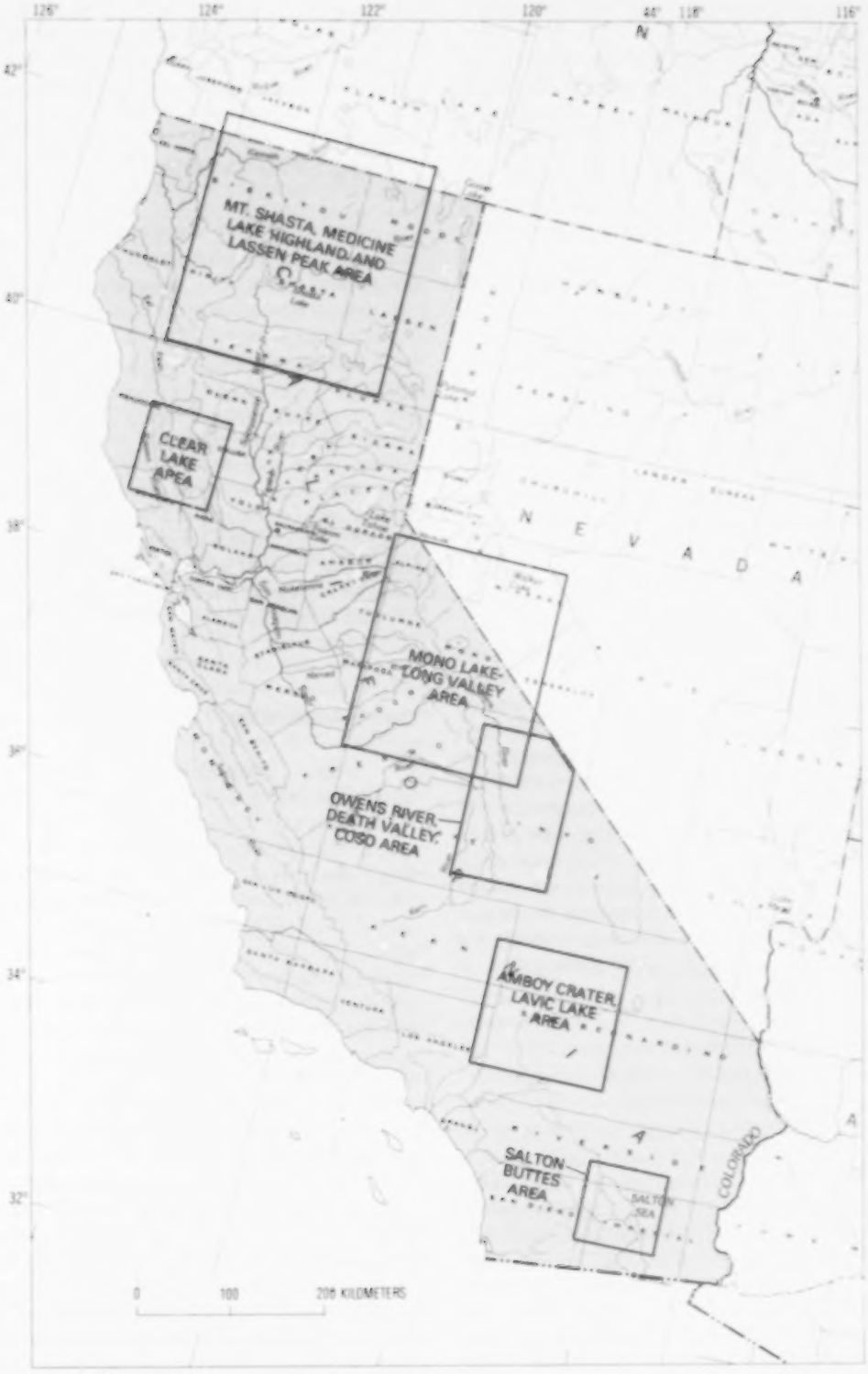


Figure 1. Areas subject to potential hazards from future eruptions in California. Areas numbered I to VI are shown in detail as separate illustrations on plate 1.

techniques (Colman and Pierce, 1977), and soil-profile development (Birkeland, 1984).[1]

Late Pleistocene and Holocene vents are further divided on the map into three general categories based on character of past eruptions and partly on composition of erupted products as follows:

1. quiet to mildly explosive volcanic vents that have erupted basaltic to basaltic-andesite lavas;
2. explosive vents that have erupted andesitic to rhyolitic lavas; and
3. volcanic vents at which explosive steam-blasts (phreatic or phreatomagmatic) have occurred.

Classification of volcanoes, based on composition of products erupted, style of eruption, or both, is useful for providing general information about the potential location, nature, and timing of future eruptions. Large, central-vent, silicic volcanoes are likely to erupt more frequently and more explosively in the future than smaller, mafic volcanoes, most of which are widely scattered in volcanic fields. Most central-vent volcanoes and silicic volcanic centers are located above large, shallow masses of differentiated magma that sporadically erupt viscous gas-rich magma and, thus, have a greater tendency to erupt explosively and repeatedly.

In contrast, vents located in mafic volcanic fields erupt less viscous magma from which gas generally escapes nonexplosively. Mafic magma may come to the surface from great depths and commonly is not stored in large chambers in the crust; such eruptions are less explosive than those at more silicic centers and are less likely to occur repeatedly from the same vent. However, mafic magmas, like silicic magmas, may interact with ground water and cause phreatic explosions. Thus, large silicic central-vent volcanoes like Mount Shasta and Lassen Peak can be expected to erupt repeatedly in the future; however, eruptions in mafic volcanic fields probably will occur at new vents within the field rather than at previously active vents.

TYPES OF POTENTIALLY HAZARDOUS EVENTS

Many kinds of volcanic events directly or indirectly endanger people as well as various kinds of property around volcanoes. These events can be conveniently grouped under three headings: (1) flowage phenomena, (2) eruption of tephra, and (3) emission of volcanic gases (table 1). This section describes volcanic processes and their consequences to provide a background for the following discussions of volcanic-hazard zonation and mitigation of volcanic hazards. Types of volcanic eruptions possible in California, and a description of associated hazards and effects, are shown in table 1.

[1]Where applicable, an original source is used and referenced for information about each vent. In many instances, however, I have reinterpreted or supplemented this information with my own investigations.

Flowage Phenomena

During volcanic eruptions materials are erupted into the air or onto the flanks of a volcano and move downslope under the influence of gravity. These materials move or flow away from a volcano either on its flanks or down valleys leading away from the volcano. Such flowage phenomena may consist solely of lava or mixtures of lava blocks, lapilli, and ash mixed with gases and or water (hot or cold). Depending on their composition, temperature, the slopes involved, and other factors, flows may move at high or low speeds. Some flows stay in topographic lows as they move from a volcano and can be avoided by climbing out of lows and valleys; others affect high and low topography alike and cannot be avoided once an eruption begins. The full range of flowage phenomena is described below in terms of their origin, deposits, effects, and occurrences in California.

Debris Avalanches

Debris avalanches are flowing or sliding, incoherent and chaotic, wet or dry mixtures of soil and rock debris that move away from their source at high speed. Volcanic-debris avalanches occur occasionally at large central-vent volcanoes and are among the most hazardous of volcanic events. Such avalanches form when part of a volcanic edifice fails catastrophically and moves downslope away from the volcano. Disruption of a volcanic cone may be the result of intrusion of magma and earthquake shaking, as at Mount St. Helens in 1980 (Voight and others, 1981), or of a volcanic blast as apparently occurred at Bezymianny in Kamchatka, U.S.S.R., in 1956 (Gorshkov, 1959; Bogoyavlenskaya and others, 1985). Steep-sided volcanic cones may also fail due to the influence of gravity after gradual weakening by hydrothermal alteration.

Debris avalanches produce thick, hummocky deposits that can extend as far as several tens of kilometers from a volcano and cover an area of a few tens of square kilometers, as occurred at Mount St. Helens in 1980, to a few hundred square kilometers, as occurred at Mount Shasta between 300,000 and 360,000 yr ago (Crandell and others, 1984). Debris avalanches are most likely at steep-sided volcanoes and, thus, are a potential hazard primarily at Mount Shasta, Lassen Peak, and possibly Mammoth Mountain in Long Valley.

The avalanche from Mount Shasta flowed northwesterly a distance of about 45 km and the deposit covers an area of at least 450 km^2. A late-Pleistocene avalanche at Mammoth Mountain was considerably smaller and traveled less than 6 km from its source (Lipshie, 1976). About 300 yr ago, three rockfall-debris avalanches occurred from domes at the Chaos Crags eruptive center near Lassen Peak (Crandell and others, 1974). The Chaos Crags avalanches traveled as far as 4.3 km from their source areas.

Debris avalanches destroy everything in their paths by impact or burial beneath tens of meters of debris. Because debris avalanches occur with little warning and can travel at high speeds, areas that might be affected should be evacuated *before* such avalanches occur. Therefore, local government officials might decide to evacuate some areas in advance of a threatened eruption.

Pyroclastic Flows

Pyroclastic flows are masses of hot, dry rock fragments, mixed with hot gases, that move away from their source vents at high speeds. They may result from explosive eruption of molten or solid rock fragments, or both, along with gas, or from the collapse of vertical eruptive columns of rock fragments, ash, and gases. Pyroclastic flows may also result from a laterally directed explosion or collapse of hot rock debris from a dome or lava flow. Rock fragments in pyroclastic flows may range widely in grain size and consist mostly of dense rock debris or of pumice fragments. Pyroclastic flows can travel downslope at speeds of 50 to more than 150 km/hr, their velocity depending largely on their volume and on the steepness of slopes over which they travel. Pyroclastic flows commonly contain gases and rock debris with temperatures of several hundred degrees Celsius.

Most pyroclastic flows consist of two parts: a basal flow of coarse fragments that moves along the ground and a turbulent cloud of finer particles (ash cloud) that rises above the basal flow. Ash in the cloud may fall over a wide area adjacent to the basal flow.

Pyroclastic flows generally follow valleys or other depressions but can have enough momentum to overtop hills or ridges in their paths. The larger the mass and faster a flow travels, the higher the flow will rise onto obstacles in its path.

Pyroclastic flows are extremely hazardous because of their high speeds and high temperatures. Objects and structures in their paths are generally destroyed or swept away by the impact of debris or by associated hurricane-force winds. Wood and other combustible materials are commonly burned by contact with hot debris and gases. In addition to death or injury caused by impact by the basal flow, people and animals may also be burned or be killed in nearby areas and around the margins of a pyroclastic flow by inhalation of hot ash and gases. During an eruption of Mount Pelée on Martinique in 1902, a cloud of hot ash and gases swept into the town of St. Pierre at an estimated speed of 160 km/hr or more (Macdonald, 1972). About 30,000 people died within minutes, most of them from inhalation of hot ash and gases. A similar explosive eruption of Mount Lamington, New Guinea, in 1951 produced clouds of hot ash that swept down all sides of the volcano at high speeds, killed about 3,000 people, and destroyed nearly everything within an area of about 230 km^2 (Taylor, 1958).

Pyroclastic flows have been erupted repeatedly at several volcanic centers in California during Holocene time (table 2). Pyroclastic flows at Mount Shasta flowed down all flanks of the volcano, and some extended more than 20 km from the summit. Based on the mobility of past pyroclastic flows at Mount Shasta, calculations suggest that future pyroclastic flows may extend as far as 30 km from the summit (Miller, 1980). Pyroclastic flows in the Lassen and Mono Lake–Long Valley regions have been erupted repeatedly from several vents and some have moved as far as 10–15 km (Crandell and others, 1974; Miller and others, 1982). Future pyroclastic flows like those of the past will be extremely hazardous and devastating. Moreover, the probable existence of large magma chambers beneath several volcanic areas in California suggests that pyroclastic flows considerably larger than past events are possible. Such pyroclastic flows would be extremely destructive over wide areas. Because pyroclastic flows move at such high speeds, escape is not possible once they form; to avoid loss of life, local government officials may decide to evacuate areas subject to pyroclastic flows *before* they occur.

Directed Blasts

Directed blasts consist of an inflated mixture of hot rock debris, ash, and gases that may be hundreds of meters thick and that moves at high speed along the ground surface with little or no control by the underlying topography. Directed blasts are among the most destructive of volcanic phenomena because within a few minutes they can devastate areas of tens to hundreds of square kilometers and kill virtually all living things in these areas by abrasion, impact, burial, and heat. Most such blasts occur when viscous gas-rich magma is emplaced at shallow levels in a volcano. Directed blasts may affect only narrow arcs or may spread out from a volcano to cover a sector as broad as 180° of arc, and they can reach distances of several tens of kilometers from a vent (Crandell and Hoblitt, 1986). If blasts are vertically directed, they may affect all sides of a volcano (Taylor, 1958). Blasts are known to reach speeds of up to 600 km/hr. The resulting deposits form a blanket of blocks,

lapilli, and ash that thins from a few meters near the source to a few centimeters near the margin.

A directed blast at Mount St. Helens, Wash., in 1980, devastated an area of 600 km^2 out to a distance of 28 km from the volcano and killed more than 60 people. A similar blast in 1956 at Bezymianny volcano, U.S.S.R., affected an area of about 500 km^2 out to a distance of 30 km from the volcano (Gorshkov, 1959; Bogoyavlenskaya and others, 1985). Both events were associated with debris-avalanches and formed large horseshoe-shaped craters open in the direction of the blast. Two small directed blasts (Eppler, 1987) or pyroclastic flows (R. L. Christiansen, and M. A. Clynne, written commun., 1986) occurred at Lassen Peak in 1915 (table 2). The events destroyed the forest in a narrow sector north-northeast of the volcano to a distance of about 5 km.

Future blasts are most likely to occur at steep-sided volcanoes like Mount Shasta and Lassen Peak. The possibility of a blast, and the sector around a volcano that may be affected, can often be anticipated by an extended period of precursory seismicity and the nature of deformation of the volcano; people should be evacuated by the local government officials from such areas *prior* to a blast because blasts can occur with little or no immediate warning and move at speeds that preclude escape.

Pyroclastic Surges

Pyroclastic surges are turbulent, low-density clouds of rock debris and air or other gases that move over the ground surface at high speed. They typically hug the ground and, depending on their density and speed, may or may not be controlled by the underlying topography. Pyroclastic surges are of two types: "hot" pyroclastic surges that consist of "dry" clouds of rock debris and gases that have temperatures appreciably above 100°C, and "cold" pyroclastic surges, also called base surges, that consist of rock debris and steam or water at or below a temperature of 100°C. Both types of pyroclastic surges destroy or remove structures and vegetation by impact of rock fragments moving at high speeds and may bury the ground surface with a layer of ash and coarser debris. Because of their high temperatures, hot pyroclastic surges may start fires and kill or burn people and animals. Both types of surges can extend as far as 10 km from their source vents and devastate life and property within their paths.

Pyroclastic surges have occurred in the past (table 2) and can be expected to occur again at many volcanic centers in the State. Future cold pyroclastic surges (base surges) are considered more likely to occur at volcanic vents near lakes, those that have crater lakes, and at vents in areas having a shallow water table than in areas where magma cannot come in contact with water. Local government officials may decide to evacuate some areas *in advance* of such events because pyroclastic surges move with such high speeds, people cannot escape once they begin.

Lava Flows

Lava flows are streams of molten rock that erupt relatively nonexplosively from a volcano and move slowly downslope. The distance traveled by a lava flow depends on such variables as the viscosity of the lava, volume erupted, steepness of the slope, and obstructions in the path of the flow. Basalt flows may reach 50 km from their sources, but few andesite flows extend more than 10–15 km. Because of their high viscosity, dacite and rhyolite lava extrusions typically form short, thick flows or domes.

Lava flows cause extensive damage or total destruction by burning, crushing, or burying everything in their paths. They need not directly threaten people, however, because they usually move a few meters to a few hundred meters per hour, and their paths of movement can be at least roughly predicted. Lava flows that move onto snow or ice can cause destructive debris flows and floods, and those that move into forests can cause fires. The flanks of lava flows typically are unstable during their growth and collapse repeatedly, occasionally producing explosive blasts and (or) small pyroclastic flows.

Lava flows have been erupted at many vents in California during Holocene time (table 2); their compositions have ranged from basalt to rhyolite, and the lengths and other characteristics of flows vary accordingly. Lava flows of a variety of compositions are likely to erupt again in California, and all nonmovable objects in their paths will be endangered. Accordingly, local government officials may ask for prompt evacuation of areas likely to be affected.

Lava Domes

Volcanic domes are masses of solid rock that are formed when viscous lava is erupted slowly from a vent. If the lava is viscous enough, it will pile up above the vent to form a dome rather than move away as a lava flow. The sides of most domes are very steep and typically are mantled with unstable rock debris formed during or shortly after dome emplacement. Most domes are composed of silica-rich lavas that have a lower gas content than do the lavas erupted earlier in the same eruptive sequence; nevertheless, some dome lavas still contain enough gas to cause explosions within a dome as it is being formed.

The direct effects of dome eruption include local burial or disruption of the preexisting ground surface by the dome itself and widespread burial by rock debris if

part of the dome collapses. Because of their high temperatures, domes may start fires if they are erupted into forests. Domes are extruded so slowly that they can be avoided by people, but they may endanger structures that cannot be moved. The major hazard associated with domes, however, is from pyroclastic flows produced by explosions or collapses. These pyroclastic flows can occur without warning and move very rapidly, endangering life and property up to 20 km from their sources.

Domes ranging in composition from dacite to rhyolite have erupted on numerous occasions during Holocene time in the Mount Shasta, Medicine Lake, Lassen Peak, and Mono Lake–Long Valley areas (table 2). Domes of similar compositions have also erupted during late Pleistocene time at numerous centers in California. Domes at Mount Shasta and Lassen Peak have collapsed or exploded on several occasions to produce hot pyroclastic flows, some extending as far as 18 km from their sources. Lines of domes, erupted at the Medicine Lake volcano and at the Inyo volcanoes about 1,200 yr ago and between about 800 and 600 yr ago, appear to have been formed over short intervals of time when vertical tabular dikelike magma bodies approached the surface (Fink and Pollard, 1983; Miller, 1983, 1985). At most vents in California, dome emplacement followed more explosive eruptions. Future domes are also likely to be erupted late in an eruptive cycle.

Debris Flows

A debris flow (sometimes called mudflow) is a flowing mixture of water-saturated debris that moves downslope under the force of gravity. Debris flows consist of material varying in size from clay to blocks several tens of meters in maximum dimension. When moving, they resemble masses of wet concrete and tend to flow downslope along channels or stream valleys. Debris flows are formed when loose masses of unconsolidated wet debris become unstable. Water may be supplied by rainfall, by melting of snow or ice, or by overflow of a crater lake. Debris flows may be formed directly if lava or pyroclastic flows are erupted onto snow and ice. Debris flows may be either hot or cold, depending on their manner of origin and the temperature of their constituent debris.

Debris flows can travel great distances down valleys, and debris-flow fronts can move at high speeds—as much as 85 km/hr. Debris flows produced during an eruption of Cotopaxi volcano in Ecuador in 1877 traveled more than 320 km down one valley at an average speed of 27 km/hr (Macdonald, 1972). High-speed debris flows may climb valley walls on the outsides of bends, and their momentum may also carry them over obstacles. Debris flows confined in narrow valleys or by constrictions in valleys can temporarily thicken and fill valleys to heights of 100 m or more (Crandell, 1971).

The major hazard to human life from debris flows is from burial or impact by boulders and other debris. People and animals also can be severely burned by debris flows carrying hot debris. Buildings and other property in the path of a debris flow can be buried, smashed, or carried away. Because of their relatively high density and viscosity, debris flows can move and even carry away vehicles and other objects as large as bridges and locomotives.

Because debris flows are confined to areas downslope and downvalley from their points of origin, people can avoid them by seeking high ground. Debris-flow hazard decreases gradually downvalley from possible source volcanoes but more abruptly with increasing altitude above valley floors. People seeking to escape should climb valley sides rather than try to outrun debris flows in valley bottoms. During eruptive activity or precursors to eruptions, local government officials may ask for prompt evacuation of areas likely to be affected.

Debris flows have occurred repeatedly during eruptions at snow-covered volcanoes in California during Holocene time (table 2). The largest debris flows have occurred at Mount Shasta and Lassen Peak. At Mount Shasta, debris flows have gone down all flanks of the volcano, some to distances of more than 30 km. Debris flows at Lassen have generally been smaller than at Shasta, presumably because the volcano is smaller and has no glaciers and less snow cover; some small- to moderate-sized debris flows formed during eruptions in 1915. Small debris flows have been generated occasionally by eruptions of hot debris from the Mono and Inyo volcanoes onto winter snowpacks. Debris flows at large ice- and snow-covered volcanoes like Mount Shasta can be expected more frequently and will be larger in size than at other volcanic centers in California.

Floods

Floods related to volcanism can be produced by melting of snow and ice during eruptions of ice-clad volcanoes like Mount Shasta and by heavy rains that may accompany eruptions. Floods carrying unusually large amounts of rock debris can leave thick deposits of sand and gravel at and beyond the mouths of canyons and on valley floors leading away from volcanoes. Eruption-caused floods can occur suddenly and can be of large volume; if rivers are already high because of heavy rainfall or snowmelt, such floods can be far larger than normal. Danger from them is similar to that from floods having other origins, but floods caused by eruptions may be more damaging because of an unusually high content of sediment. Floods can also be generated by eruption-

caused seiches (waves) that could overtop dams or move down outlet streams from lakes.

Eruption-caused floods in California are likely to occur more frequently and be larger in volume at Mount Shasta, and possibly Lassen Peak, than at other vents. Small-volume floods could also occur at other volcanic centers in California if hot debris is erupted onto thick blankets of snow or into river systems. Future floods at Mount Shasta may extend down the Sacramento River to Shasta Lake and down the Shasta and Klamath Rivers. Eruptions in Clear Lake could produce seiches that could overtop the dam at the southeast end of the lake and cause flooding down Cache Creek and into the Sacramento River valley.

Eruption of Tephra

During many volcanic eruptions, fragments of lava or rock are blasted into the air by explosions or carried upward by a convecting column of hot gases. These fragments fall back to earth on and downwind from their source vent to form a pyroclastic-fall or "ash" deposit. Pyroclastic-fall deposits, referred to as tephra, consist of combinations of pumice, scoria, dense-rock material, and crystals, that range in size from ash (<2 mm) through lapilli (2–64 mm) to blocks (>64 mm). Eruptions that produce tephra range from short-lived weak ones that eject debris only a few meters into the air, to cataclysmic explosions that throw debris to heights of several tens of kilometers. Explosive eruptions that produce voluminous tephra deposits also commonly produce pyroclastic flows.

Close to an erupting vent, the main hazards to property posed by eruptions of tephra include high temperatures, burial, and impact of falling fragments; large falling blocks can kill or injure persons who cannot find shelter. Significant property damage can result from the weight of tephra, especially if it is wet, and 20 cm or more of tephra may cause structures to collapse. Hot tephra falling near a volcano may set fire to forests and structures. Farther away, the chief danger to life is the effect of ash on the respiratory system. Even 5 cm of ash will stop the movement of most vehicles and disrupt transportation, communication, and utility systems. Machinery is especially susceptible to the abrasive and corrosive effects of ash. These effects, together with decreased visibility or darkness during an eruption, may further disrupt normal transportation, communication, and electrical services; they can also result in psychological stresses and panic among people whose lives may not be endangered.

A wide variety of compositions and volumes of tephra have been erupted during the last 10,000 yr in California (table 2). Silicic volcanic centers like those at the Medicine Lake and the Mono-Inyo volcanoes have produced many lobe-shaped tephra deposits, some of which extended hundreds of kilometers downwind. Such eruptions are likely to occur in the future at those and other silicic volcanoes like Mount Shasta and Lassen Peak.

Eruptions of relatively small volumes of basaltic tephra have occurred at many vents during Holocene time. Such eruptions have been far less explosive than more silicic eruptions and have produced cinder cones at the vents and tephra deposits within a few kilometers downwind. Similar small-volume eruptions of tephra can be expected to occur again at many vents within mafic volcanic fields in California.

Emission of Volcanic Gases

All magmas contain dissolved gases that are released during eruptions as well as between eruptive episodes. Gas emission often precedes eruptions, and gases can issue from fumaroles for hundreds or thousands of years after an eruption has ended.

Volcanic gases usually consist predominantly of steam, followed in abundance by carbon dioxide and compounds of sulfur and chlorine. Minor amounts of carbon monoxide, fluorine and boron compounds, ammonia, and several other compounds are found in some volcanic gases.

Distribution of volcanic gases is mostly controlled by the wind; gases may be concentrated near a vent but become diluted rapidly downwind. Even very dilute gases can have a noticeable odor and can harm plants and some animals tens of kilometers downwind from a vent.

Close to a vent, volcanic gases can endanger life and health as well as property. Acids and ammonia and other compounds present in volcanic gases can damage eyes and respiratory systems of people and animals, and accumulation in closed depressions of gases heavier than air, like carbon dioxide, can suffocate people or animals that enter such basins. Other harmful effects of volcanic gases on plants and animals, and corrosion of metals and other property, can be severe near and downwind from especially active vents.

Fumarolic activity and associated hot-spring activity are widespread at many volcanic centers in California. Future eruptions will undoubtedly release large quantities of gases that, at least near the volcano, may be dangerous.

VOLCANIC-HAZARD ZONATION AT HOLOCENE VOLCANIC CENTERS

Areas likely to be affected by future volcanism in California are subdivided into hazard zones on the basis

of past eruptions at volcanoes in those areas or of past eruptions at similar volcanoes elsewhere in the western United States. Except for the Salton Buttes area, hazard zones are shown only for volcanic centers that are known or inferred to have been active during Holocene time.[2] Eruptions could occur at some volcanic areas in California that have not been active during Holocene time, but the probability of eruptions in those areas during the next few centuries is so low that hazard assessments have not been attempted.

The outer boundaries of hazard zones are generalized and enclose minimum areas that would be endangered by eruptions like those used as models. Within these zones, relative hazard is gradational and decreases with increasing distance from a vent and for most flowage phenomena with increasing height above valley floors or basins.

The various hazard zones depicted show differences in the possible kinds and extents of hazards. Hazard zones termed "locally precedented" at a given volcano are based on events that have occurred at that volcano during the last 10,000 yr. A pyroclastic-flow-hazard zone termed "locally unprecedented" is shown at some silicic volcanic centers where large, shallow, differentiated magma chambers are thought to exist and where explosive eruptions larger than any identified at that volcano in the past are thought to be probable enough to consider in hazard planning. The eruption of Mount Mazama (at Crater Lake, Oreg.) about 6,800 yr ago serves as a model to define the extent of hazards from pyroclastic flows at these centers. Although hazard zones are based on specific, identified "model" events, the size, location, or nature of the next eruption in California are impossible to forecast.

An inverse relationship exists between the size of eruptions (volume of material ejected) and their frequency; like earthquakes, small eruptions occur more frequently than large ones. Studies of past eruptive activity at Mount St. Helens (Crandell and Mullineaux, 1978, p. 17), for example, suggested that a tephra eruption of small volume can be expected there as often as once every 100 yr. An eruption of moderate volume might occur once every 500–1,000 yr, and a significantly larger eruption no more than about once every 2,000–3,000 yr. A few even larger, cataclysmic eruptions have occurred in the western United States during the last 2 m.y., including one in Long Valley, Calif., about 700,000 yr ago (Bailey and others, 1976). These very large eruptions deposited ash over much of the western United States. Such cataclysmic eruptions are very infrequent, however, and are difficult to plan for. Tephra-hazard zones for locally unprecedented eruptions are briefly discussed in the section titled Tephra-Hazard Zones.

Flowage-Hazard Zones

Combined Flowage-Hazard Zone for Locally Precedented Events

A hazard zone based on a combination of locally precedented flowage events is shown at each of five andesitic to rhyolitic volcanic centers in California (see plate 1, maps I, III, VI). The hazard zones for each volcanic center are composites of zones drawn around each Holocene silicic vent and, thus, vary in size and shape. The hazard zones depict areas most likely to be affected by future lava flows and domes, by pyroclastic flows and surges, by lateral blasts, and at some volcanoes, by debris flows and floods. Although not all parts of hazard zones depicted at each volcano have been affected by flowage events during Holocene time, any area within a zone could be affected during future eruptions that are as extensive as those of the past 10,000 yr.

At Mount Shasta the combined flowage-hazard zone extends to about 25 km from the summit toward the northwest and southeast but is less extensive to the southwest and northeast where topographically high areas will restrict the distribution of flowage phenomena. However, clouds of hot ash associated with future pyroclastic flows could extend for a few kilometers beyond the limit of the zone into topographically high as well as low areas. Not shown at Mount Shasta are hazard zones for very large directed-blast and debris-avalanche events. Although possible at Mount Shasta, such catastrophic events are very infrequent. The sector around a volcano that might be affected by such events is difficult to forecast. If such events were to occur, any sector around the volcano could be devastated out to distances of as much as 30 and 45 km for directed blasts and debris avalanches, respectively. Catastrophic debris-avalanche and directed-blast events probably will be preceded by recognizable precursors. Thus, monitoring at large, steep-sided volcanoes like Mount Shasta may allow hazard zones depicted here to be modified prior to the occurrence of such catastrophic events.

A combined flowage-hazard zone is drawn out to a radius of 10 km from Holocene silicic vents in the Medicine Lake area. The outer boundary of the zone is

[2]A combined flowage-hazard zone is shown for the Salton Buttes rhyolite domes, even though the youngest eruptive activity there has been dated by potassium-argon at 16,000 yr ± 40,000 (Muffler and White, 1969; Robinson and others, 1976). A hazard zone has been plotted for this area because: (1) eruptive activity possibly may be younger than 16,000 yr old; (2) the Salton Buttes vents exhibit bimodal basalt-rhyolite volcanism and at least some future volcanic activity probably will be explosive; and (3) the Salton Buttes area is a region of active and rapid crustal spreading and, thus, is a likely place for future movement of magma toward the surface.

drawn without regard to topography because blasts and surges can affect areas as far as 10 km from a vent regardless of the topography. A 10-km outer boundary for combined flowage hazards is shown here rather than the 25-km outer boundary shown at Mount Shasta, because of the differences in the nature of precedented eruptions in the two areas. In the Medicine Lake area, future eruptions are likely to generate pyroclastic flows within this zone, even though pyroclastic flows have not been identified among Holocene eruptive deposits from these vents.

A combined flowage-hazard zone with a radius of 10 km has been drawn around Holocene silicic vents at Lassen Peak. The shape and outer boundary of the zone are not controlled by topography for reasons discussed above.

A combined flowage-hazard zone that extends out to 15 km is drawn around silicic vents in the Mono Lake–Long Valley region that have been active during Holocene time. The shape of the outer boundary of the zone is modified by high ground on the west and south that would restrict the extent of future flowage phenomena. A flowage-hazard zone with a radius of 15 km is also drawn around a 7-km-long, narrow, west-trending zone in the southern part of the caldera. No eruptions have occurred in this part of Long Valley caldera during Holocene time; the radius of the flowage-hazard zone is based on small-moderate sized explosive eruptions that have occurred in the Mono-Inyo volcanic chain during the last several thousand years. This possible vent zone includes the epicenters of swarms of earthquakes and the locus of extensional deformation during 1982–1985 and is a possible site of future eruptive activity (Miller and others, 1982; Miller, 1985). Thus, this zone could be affected by pyroclastic flows and surges, blasts, lava flows, and domes during a future eruption.

A combined flowage-hazard zone with a radius of 10 km is shown around rhyolite vents in the Salton Buttes area. Although the youngest eruptions in this area are not known to have produced pyroclastic flows and surges, the compositions of lavas of past eruptions and the association of vents with ground water and the Salton Sea suggest that pyroclastic flows and surges and explosive eruptions could occur in the future. Such events commonly are destructive out to distances of at least 10 km from an active vent.

Hazard Zone for Locally Unprecedented Pyroclastic Flows

Pyroclastic eruptions considerably larger than locally precedented (Holocene) events are considered possible at Mount Shasta, Medicine Lake volcano, Lassen Peak, and in the Mono Lake–Long Valley area because of the inferred presence of highly differentiated magma chambers and (or) local eruptive histories that suggest that the volcanic systems may be evolving toward future large-volume eruptions. Such eruptions could produce pyroclastic flows much larger than any that have occurred in the past at these vents during the Holocene. A hazard zone with a radius of 40 km has been drawn around silicic vents in each of these four areas. This distance is based on the Mount Mazama eruption that occurred at the site of Crater Lake, Oreg.; ash flows from that eruption extended out in a broad fan to about 40 km around the vent and extended as far as about 65 km down valleys leading away from the volcano. Eruptions as devastating as this one occur very infrequently but could occur and have wide-reaching destructive effects at several locations in California.

Two additional areas in California, the Coso and Clear Lake areas, have the potential of producing large and unprecedented explosive eruptions. Although explosive silicic eruptions have not occurred at either location during the Holocene, silicic magma chambers are thought to underlie both areas (Bacon, 1985; Hearn and others, 1975). Hazard zones for locally unprecedented pyroclastic flows have not been shown for either area, however, because little is known about the size, nature, or composition of possible magma chambers and the likelihood of future large eruptions is unknown.

Hazard Zone for Locally Precedented Debris Flows

Zones of debris-flow hazard in valleys leading away from Mount Shasta and Lassen Peak include areas subject to debris flows from future eruptions similar to the largest event of the last 10,000 yr at each vent. *These hazard zones are shown only where they extend beyond the combined flowage-hazard zone*. Such debris-flow-hazard zones extend downvalley only to major rivers or major bodies of water; they are expected to become muddy floods beyond the zones depicted.

Hazard Zone for Locally Precedented Lava Flows and Domes

Zones of potential hazard from mafic lava flows are shown on the accompanying maps for fields of vents in five areas of California (plate 1: maps I, III, IV, V). The zones delineate areas that may be affected by future eruptions, similar to the largest ones of the last 10,000 yr in that area, and include areas that are downslope from vents active during Holocene time. *These zones are shown*

only where they extend beyond the combined flowage-hazard zone. Parts of these zones are also subject to falls of cinders and ballistic blocks.

Hazard Zone for Pyroclastic Surges

Zones of potential hazard from future steam blasts and pyroclastic surges are shown for the Clear Lake and Ubehebe Crater areas. The zones have a 10-km radius around vents in these two areas that have produced these types of eruptions during Holocene time. Pyroclastic surges may also occur at other vents in California where a combined flowage-hazard zone is shown, although a separate surge-hazard zone is not shown at these locations.

Flood-Hazard Zone

Hazard zones from future floods are shown extending from the Mount Shasta, Lassen Peak, and Mono Lake-Long Valley volcanic centers. *These flood-hazard zones are shown only where they extend beyond combined flowage-hazard zones or debris-flow-hazard zones.*

Tephra-Hazard Zones

Tephra and gases from eruptions are carried away from the vent by prevailing winds. The location and extent of hazard zones for air-fall deposits are determined by the volume of the eruption, the height of the eruption column, and the direction and speed of prevailing winds. For any eruption of a given volume and column height, the likelihood that ash will affect a site depends on the frequency with which winds at various heights above the volcano blow toward the site; the thickness of ash that will fall at the site is chiefly a function of volume erupted and windspeed.

Wind-direction and windspeed frequencies can be judged from past ash falls and from modern wind records. The majority of ash beds erupted at volcanoes in California lie east of their source vents. Furthermore, at well-studied Pacific Northwest volcanoes like Mount Rainier and Mount St. Helens, more than 90 percent of the ash beds erupted during the last 10,000 yr lie east of those volcanoes (Mullineaux, 1976). The ash beds also extend farther east of the volcanoes than to the west. These data suggest that most tephra from future eruptions will likewise be deposited east of vents.

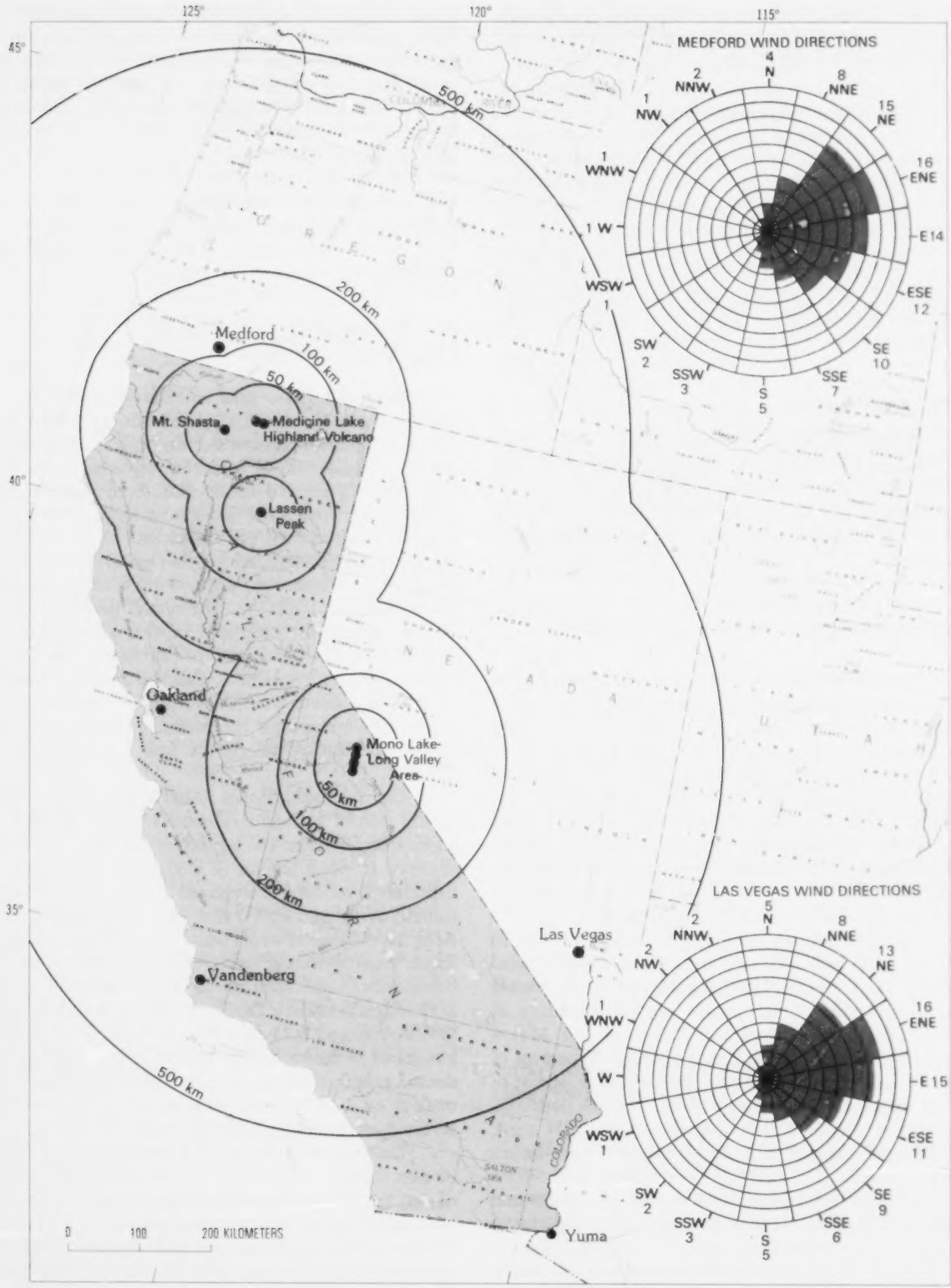
Modern wind records show wind patterns that resemble data obtained from the distribution of ash beds. Twenty-year records from 1950 to 1970 for several locations in the western United States indicate that winds blow toward a direction that is east of a north-south line about 85 percent of the time. Figure 2 shows wind-direction frequencies at Medford, Oreg., and Las Vegas, Nev.; wind patterns at Oakland and Vandenberg Air Force Base, Calif., and Yuma, Ariz., are very similar and are not shown. The records also show that windspeeds toward the east are about twice those toward the west. The correspondence between the distribution of ash beds and records of windspeed and direction suggests that winds blowing toward the east have been the pattern for thousands of years and that modern wind records may be used to estimate future wind directions and ash distributions.

Tephra-Hazard Zones for Locally Precedented Eruptions

The locations and extents of hazards from tephra as shown on maps I–VI (plate 1) are based on precedented tephra thickness versus distance for each volcanic center; the part of each circular tephra-hazard zone that will be most seriously affected during a future eruption depends on prevailing windspeeds and wind directions during the eruption. Potential ash-fall thicknesses at two distances (zones X and Y) from each vent are based on the volume of the largest tephra eruption at each volcanic center during the last 10,000 yr. The actual thickness versus distance values for eruptions of various volumes are derived from measurements of ash layers with similar volumes erupted at various Cascade-Range volcanoes. At a given distance from the volcano, the ash-thickness values shown represent the probable thickest part of a future ash blanket (along the axis of a lobe-shaped deposit).

Circular hazard zones X and Y show areas subject to ash falls of various thicknesses that are possible at silicic volcanic vents. The boundaries of zone X lie at the distance at which 20 cm of compacted ash would be expected from future eruptions similar to the largest ashfalls in the past 10,000 yr. The boundaries of zone Y lie at the distance at which 5 cm of compacted ash might result from a similar event. Ash deposits inside the boundaries of each zone will be thicker than ash deposits at the outer boundary. Significant effects from future ash falls may extend far beyond the boundaries of zone Y. Eruptions of lesser volume than the maximum precedented eruption will occur more frequently than larger ones at each center and will have effects that are less severe than those shown on the map (plate 1).

Only a part of each tephra-hazard zone is likely to be affected by a single eruption. The bulk of the volume of past ash falls at most silicic vents in California and at Mount St. Helens forms narrow elongate bands or lobes. Most eruptions in California should deposit tephra lobes of similar shape, and most of the ash would fall in a narrow sector within zone X and zone Y; lesser amounts


125°
120°
115°
45°
40°
35°
MEDFORD WIND DIRECTIONS
4 N
2 NNW
8 NNE
1 NW
15 NE
1 WNW
16 ENE
1 W
E 14
WSW 1
ESE 12
SW 2
SE 10
SSW 3
SSE 7
S 5
LAS VEGAS WIND DIRECTIONS
5 N
2 NNW
8 NNE
2 NW
13 NE
1 WNW
16 ENE
1 W
E 15
WSW 1
ESE 11
SW 2
SE 9
SSW 3
SSE 6
S 5
500 km
200 km
100 km
50 km
Medford
Mt. Shasta
Medicine Lake Highland Volcano
Lassen Peak
Oakland
Mono Lake-Long Valley Area
Las Vegas
Vandenberg
Yuma
OREGON
NEVADA
CALIFORNIA
COLORADO
SALTON SEA
0 100 200 KILOMETERS

of ash can be expected to affect a wide region around a volcanic vent. Most future lobes of ash will be deposited east of their source vents and, because windspeeds are less toward westerly directions, future lobes of ash deposited toward the west will probably be shorter than lobes of the same volume that are deposited to the east.

Tephra-Hazard Zones for Locally Unprecedented Eruptions

Eruptions of tephra considerably larger than locally precedented events are possible at Mount Shasta, Medicine Lake volcano, Lassen Peak, and the Mono Lake–Long Valley area (fig. 2). The inferred presence of shallow differentiated magma chambers and (or) local eruptive histories suggests that these systems may be evolving toward large-volume (tens of cubic kilometers) or very large volume (hundreds of cubic kilometers) eruptions.

Tephra from large and very large future eruptions will accumulate downwind from vents, and, like tephra from smaller eruptions, the location and thickness of tephra at any given distance from the vent will depend on the volume erupted and on wind direction and windspeed. Thickness versus distance curves are shown in figure 3 for possible magmatic eruptions of three volumes, based on three well-studied eruptions: a 3-km^3 Mount St. Helens eruption about 3,000 yr ago; a 40-km^3 Mount Mazama eruption about 7,000 yr ago; and a 600-km^3 eruption (Bishop Tuff eruption) that occurred in central eastern California about 700,000 yr ago. Circles with radii of 50, 100, 200, and 500 km are drawn around possible vents for such large eruptions (fig. 2). Possible compacted tephra thicknesses at various distances from vents in California can be determined from figure 3 for eruptions of the three sizes described above. Uncompacted newly fallen tephra may be thicker at a given distance than shown but will not be heavier. Wind directions (fig. 2) and windspeeds suggest that, like smaller eruptions, most tephra lobes from large to very large eruptions will be deposited to the east of vents, and lobes of ash will extend farther to the east than to the west.

For example, an explosive eruption of about 40 km^3 of magma at Lassen Peak could deposit about 30 cm of compacted ash at Reno, at a distance of 200 km, as can be determined from figures 2 and 3. However, the wind-rose diagrams in figure 2 indicate that Reno is downwind from Lassen Peak only about 10 percent of the time.

Figure 2 (facing page). Map showing volcanic vents in California that may produce future, large to very large explosive eruptions of tephra. Circles at various distances from vents can be compared with data in figure 3 to estimate possible thicknesses of ash falls from large eruptions of three different sizes. Wind-direction frequency diagrams are shown for Medford, Oreg., and Las Vegas, Nev. Wind-direction frequency data are similar at Oakland and Vandenberg Air Force Base, Calif., and Yuma, Ariz., but are not shown here. Wind-rose diagrams show average percentage of time, annually, that winds at six altitudes from 3,000 to 16,000 m blow toward wedge-shaped sectors centered on 16 principal compass directions above the station. Successive circles in the wind-rose diagrams represent 2-percent increments. Percentages listed around the circumference of the wind-rose diagrams are rounded to the nearest whole number. Tephra of individual eruptions will most likely fall along a narrow ellipse downwind from the vent. (Data from Winds Aloft Summary of the Air Weather Service, U.S. Air Force, available from the National Climatic Center, Ashville, N.C.)

ERUPTION PRECURSORS AND WARNING

Most volcanoes provide various types of warnings before eruptions begin. Although an explosive eruption could occur in California without warning, some premonitory events more likely will precede the next eruption. Steam-blast eruptions could occur with little or no warning as superheated water flashes to steam; magmatic eruptions, however, involve rise of magma toward the surface. Such an upward movement of magma normally will generate detectable earthquakes, may deform the ground surface, and may cause anomalous heat flow or changes in the temperature and chemistry of the ground and spring waters.

People living near volcanoes may detect premonitory events before an eruption. Both the frequency of occurrence and intensity of felt earthquakes commonly increase before eruptions begin. Eruptions may also be preceded by noticeable steaming or fumarolic activity and perhaps by new or enlarged areas of hot ground. However, most precursory changes are subtle and the most effective means of monitoring are instrumental and include a variety of geophysical, geodetic, and geochemical techniques. Seismometers are used to detect and locate earthquakes associated with the rise of magma. Swelling of the ground surface can be detected by using precision instruments and techniques that measure minute changes in slope, distance, or elevation at the ground surface. Other techniques involve measurement of changes in heat flow at a volcano by repeated infrared surveys or by direct measurements of hot spring or fumarole temperatures. Changes in the composition or relative abundances of fumarolic gases may also precede eruptions and can be detected by frequent or continuous analysis of gases.

These and other types of monitoring may be useful in detecting warning signs of an impending eruption (Unesco, 1972; Decker, 1973; Lipman and Mullineaux, 1981). However, the overall success of a monitoring

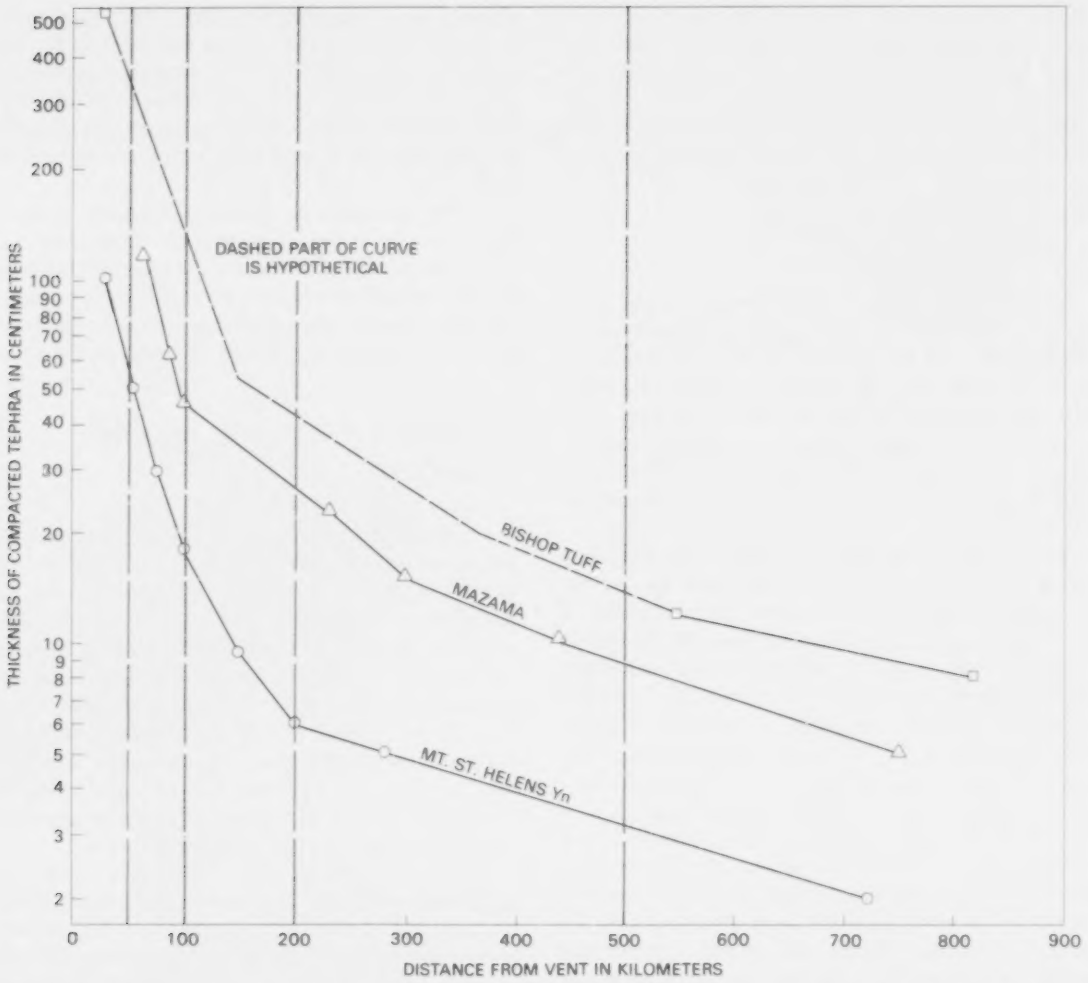


Figure 3. Plot of ash thickness versus distance for compacted ash falls from large (several cubic kilometers) to very large (hundreds of cubic kilometers) eruptions of three different sizes. Data based on individual eruptions of Mount St. Helens (volume about 3 km^3), Mount Mazama (volume about 40 km^3), and Bishop Tuff (volume about 600 km^3). Data from this figure can be compared with figure 2 to estimate possible locations and compacted thicknesses of future ash falls from large to very large eruptions in California. Data on Mount St. Helens eruption from Mullineaux, 1977; D. R. Mullineaux, written commun., 1985; Westgate and Dreimanis, 1967. Data on Mount Mazama eruption from Williams and Goles, 1968; Rai, 1971; and Mehringer and others, 1977. Data on Bishop Tuff eruption from Izett, 1982; and unpublished data of the authors.

system depends on detection and interpretation of precursory events in time to warn and evacuate people from threatened areas and to initiate other measures to mitigate the effects of the eruption. Although monitoring systems may be useful by indicating an increase in the probability of volcanic activity and its possible location, they typically do not indicate the kind or scale of an expected eruption, particularly the first magmatic event, or the surrounding areas that might be affected. Precursors to volcanic activity may continue for weeks, months, or even years before eruptive activity begins, or they can subside at any time and not be followed by an eruption. Thus, monitoring of volcanic precursors may provide a general warning that volcanic activity in a specific area is becoming more likely, but it often does not pinpoint the nature or timing of an eruption or even its certainty.

MITIGATING THE EFFECTS OF FUTURE ERUPTIONS

Future eruptions in California are certain to occur and can be neither prevented nor stopped. Future

eruptions like those of the past will vary from small, relatively nonexplosive eruptions to large and devastating eruptions; they may occur in unpopulated parts of the State or in more populated areas like Mount Shasta or Long Valley. Effective and economically feasible diversion or control of hazardous events like lava flows, pyroclastic flows, and debris flows is generally not possible. Instead, reduction of risk to life and property requires that the affected areas be avoided when possible and that plans be made to reduce the effects when and where affected areas cannot be avoided. Monitoring the most hazardous volcanoes like Mount Shasta, Medicine Lake, Lassen Peak, and the Mono Lake–Long Valley region to detect signs of an approaching eruption, and developing contingency plans to deal with the future eruptions, should help reduce risk to lives and property from future eruptions. Contingency plans can help to mitigate the adverse effects of future eruptions. To be most effective, such actions should be taken before the next eruption occurs. Local, State, and Federal agencies should develop contingency plans, at least in the areas of greatest risk, that include the following steps.

1. Evaluation of the possible effects of tephra and other eruptive products on transportation routes, communication systems, water supplies, and other critical utilities at and downwind from each volcanic center.
2. Careful evaluation of long- and short-range plans for future land use and development at and around volcanic centers in California; such plans should consider the probable effects of future eruptions at each area.
3. Installation of adequate monitoring systems at or near each of the most active and potentially most dangerous volcanic centers in California as identified in this report to measure the location and frequency of earthquakes, ground tilt, and possibly other events that might accompany the movement of magma toward the ground surface.
4. Preparation of plans to limit the access to and use of potentially hazardous areas if an eruption seems imminent, and plans for evacuation of such areas.
5. Development of emergency communications systems that can be used to warn and inform people in potentially hazardous areas to evacuate or to take other precautions.
6. Preparation of pamphlets or other means of describing official plans and procedures for dealing with volcanic eruptions. Such pamphlets should be distributed to local government officials and to the populace around each volcanic center if an eruption seems imminent, to help educate them about potential hazards. Such a pamphlet should include information on the kinds of events that might occur, their probable ranges in severity, the expected effects of those events, and what procedures can be followed to reduce risk during eruptions.

Once such preparations are completed, they should be modified as new information becomes available and land-use patterns change. Plans to deal with future eruptions should be developed on a cooperative basis by local, State, and Federal officials and agencies, and the duties and responsibilities of each group should be decided in advance of an emergency. Land-use and possible evacuation decisions during an emergency will be made by State and local officials, and persons or agencies responsible for making such critical decisions should be identified before an emergency begins. Once made, preparations like those described above may not be needed or utilized for years or even decades, but they could conceivably be needed in the near future. To be most effective, preparations must be made *before* the next eruption occurs.

ACKNOWLEDGMENTS

I am indebted to D. R. Mullineaux and D. R. Crandell for their contributions and for many thoughtful discussions during preparation of this report. The philosophical approach for volcanic-hazards zonation is modified from one developed by Mullineaux, who also provided some of the data. Crandell provided age information for many of the volcanic vents in the Lassen Peak region. I thank Duane Champion, Mike Clynne, Julie Donnelly-Nolan, R. Fleming, Roger C. Martin, Steve R. McNutt, L. J. P. Muffler, Chris Newhall, W. E. Scott, and Jim Watkins for helpful reviews.

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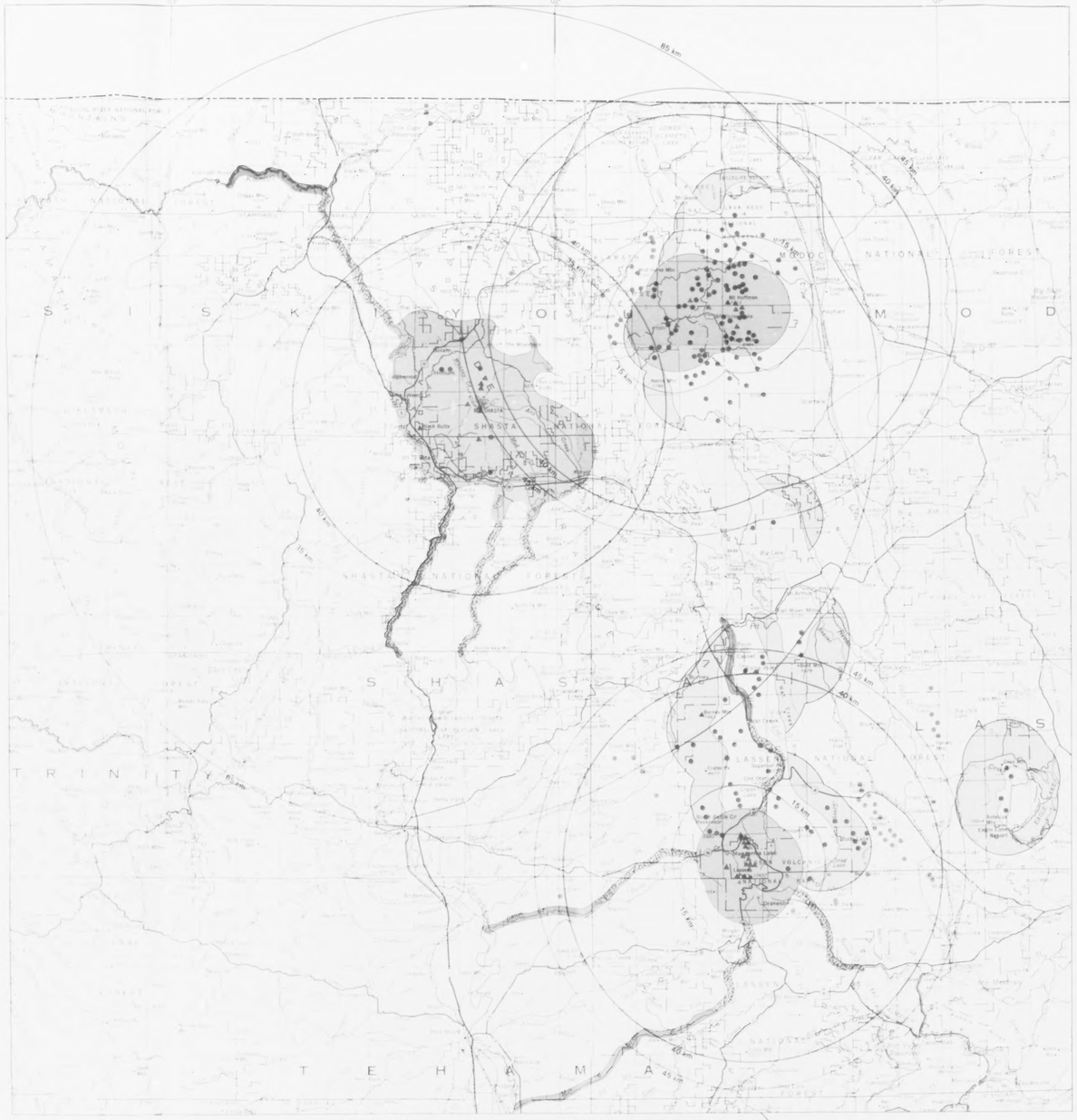
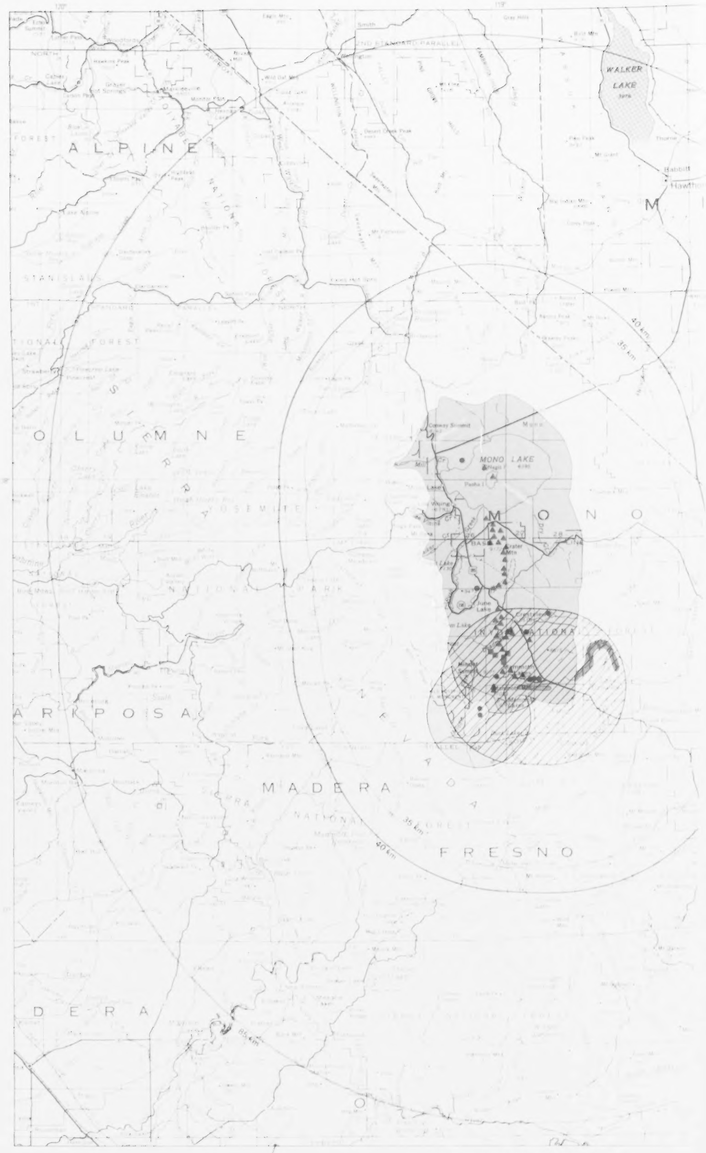
POTENTIAL HAZARDS FROM FUTURE VOLCANIC ERUPTIONS IN CALIFORNIA—U.S. Geological Survey Bulletin 1847

1847

DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY



I. MOUNT SHASTA, MEDICINE LAKE HIGHLAND, AND LASSEN PEAK AREA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Bridgeport
Walker
Yosemite
Mammoth Lakes
Devils Postpile
Minaret Summit
Mammoth Mtn
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Convict Creek
Hilton Creek
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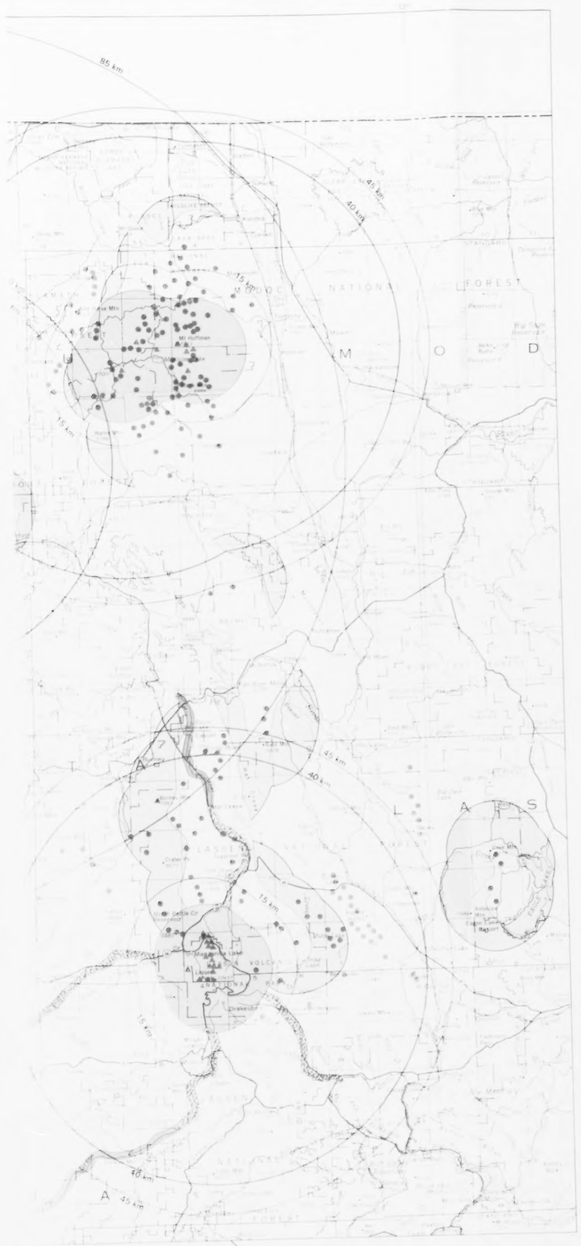
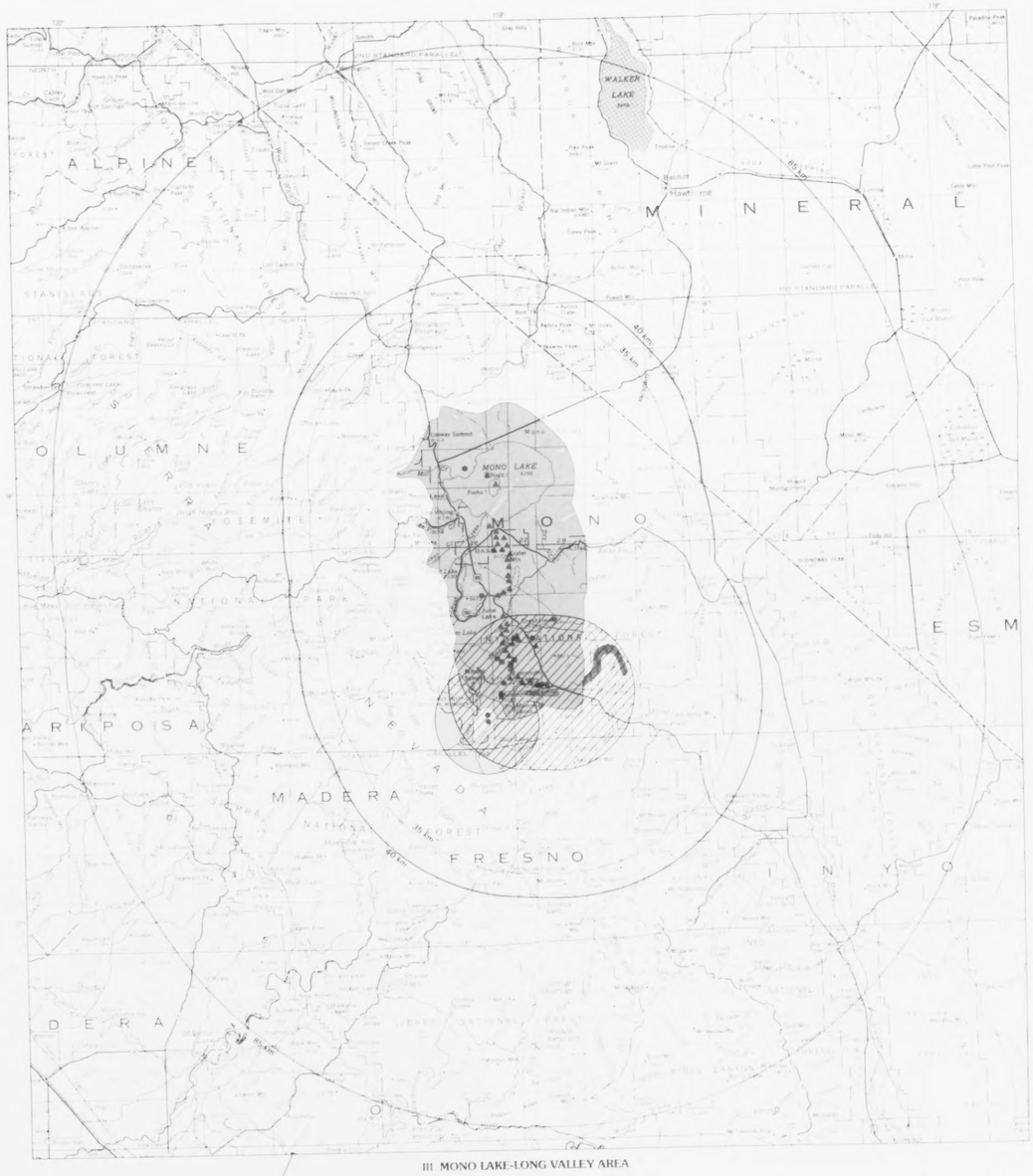
Mono Craters



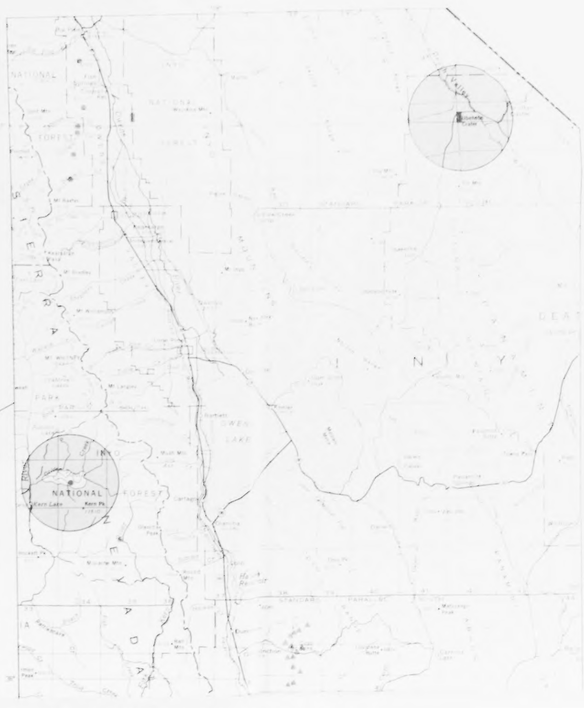
ND AND LASSEN PEAK AREA

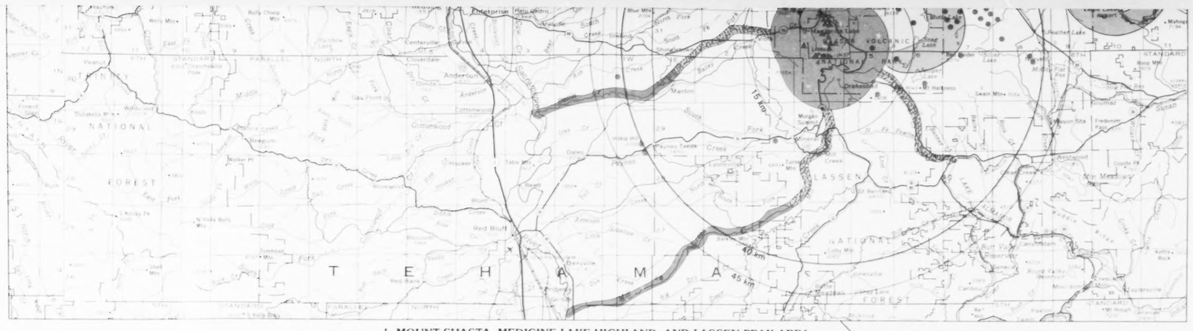


III. MONO LAKE-LONG VALLEY AREA

AREA

MT. SHASTA, MEDICINE LAKE HIGHLAND AND LASSEN PEAK AREA
CLEAR LAKE AREA
MONO LAKE-LONG VALLEY AREA
DIXIE MTS.-DEATH VALLEY (CDSI) AREA
HUNTER CRATER LAVA FLOW





I. MOUNT SHASTA, MEDICINE LAKE HIGHLAND, AND LASSEN PEAK AREA

III. MONO LAKE-LONG VALLEY AREA

EXPLANATION

DESCRIPTION OF MAP UNITS

CLASSIFICATION OF VOLCANIC VENTS

Volcanic vents are classified into two age groups, late Pleistocene and Holocene. Vents that were last active between about 100,000 and 10,000 yr ago are designated late Pleistocene. Vents active during about the last 10,000 yr are designated Holocene. Volcanic vents whose last known or inferred activity was more than about 100,000 yr ago are not shown.

Volcanic vents are also classified broadly into three categories based on style of eruption and composition of products erupted: vents that have erupted basalt and basaltic andesite, vents that have erupted andesitic to rhyolitic lavas, and vents that have erupted rock debris and steam with or without magma.

Volcanic vents of late Pleistocene age (100,000–10,000 yr B.P.)

- Mildly explosive volcanic vents which have erupted basaltic to basaltic-andesite lavas
- Explosive volcanic vents which have erupted andesitic to rhyolitic lavas
- Volcanic vents at which phreatic or phreatomagmatic eruptions have occurred

Volcanic vents of Holocene Age (< 10,000 yr B.P.)

- Mildly explosive volcanic vents which have erupted basaltic to basaltic-andesite lavas
- Explosive volcanic vents which have erupted andesitic to rhyolitic lavas
- Volcanic vents at which phreatic or phreatomagmatic eruptions have occurred

Potential volcanic-vent area in Long Valley caldera, indicated by seismicity and deformation since 1980

VOLCANIC HAZARD ZONES

Volcanic-hazard zones are shown only adjacent to vents judged to be of Holocene age except at Newberry. Older vents are thought to be extinct or to have such a long dormant interval between eruptions that no reliable estimate can be made regarding future activity and associated hazards.

Areas subject to flowage hazards

Combined flowage-hazard zone (locally precedented)—Areas adjacent to explosive volcanic vents or vents subject to eruption of domes, pyroclastic flows, and lava flows, and in some volcanoes debris flows and floods, associated with future eruptions is large as those during Holocene time at that volcano or a similar volcano in the Cascade Range. Not all parts of the hazard zone shown at each volcano have been affected by flowage events during Holocene time, but any part of the zone could be so affected in the future.

Flowage-hazard zone around possible future vents in Long Valley caldera inferred from seismicity and deformation—Areas adjacent to and within 15 km (9 mi) radius of 7 km (4 mi) long epicentral zone. This zone is subject to effects of steam blasts, pyroclastic flows and clouds of hot ash, pyroclastic surges, lava flows, and domes, and at some locations, debris flows and floods.

Pyroclastic-flow-hazard zone (locally unprecedented)—Areas subject to hot pyroclastic flows similar to the largest such events of the last 10,000 yr at a similar Cascade Range volcano. Hazard zone defined from extent of the products erupted by climactic eruptions of Mount Mazama (about 6,800 yr ago); zone is circles with a radius of 40 km (25 mi) around silicic vents in California which are considered possible sites of such a large future eruption. Pyroclastic flows as voluminous as those at Mount Mazama might affect valleys and low-lying areas as far as 65 km (40 mi) from the vent.

Volcanic debris flow (modified)-hazard zone (locally precedented)—Areas subject to volcanic debris flows from eruptions similar to the largest event of the last 10,000 yr at that specific volcano.

An unprecedented volcanic debris flow hazard zone is not shown for volcanoes in California. Generation of debris flows is largely dependent on (1) a supply of water or water stored as glacier ice, snow or (2) the availability of large volumes of hydrothermally altered and water-saturated clay-rich rock high on a volcano. The presently available source of water, the amount of hydrothermally altered debris, and the record of past events at each volcanic center in California are, therefore, better indications of future hazards from debris flows than are very large events in the past at more northern volcanoes, such as Mount Rainier, which have large glaciers and large volumes of potentially unstable hydrothermally altered rock.

Hazard zone for basaltic lava flows (locally precedented)—Areas subject to basalt or basaltic-andesite lava flows from future eruptions similar to the largest such event of the last 10,000 yr in that area. In areas of Holocene mafic and silicic volcanism, this zone is shown only where it projects beyond the combined flowage and base-surge hazard zones. Parts of this zone are also subject to falls of mafic cinders and directed blasts.

Base-surge-hazard zone—Areas around Holocene phreatic and phreatomagmatic vents that are subject to future steam blasts and base surges (table 1). Base-surge-hazard zone is shown only where it projects beyond other flowage-hazard zones.

Flood-hazard zone—Valleys beyond the extent of other flowage-hazard zones which are subject to floods caused by volcanic activity.

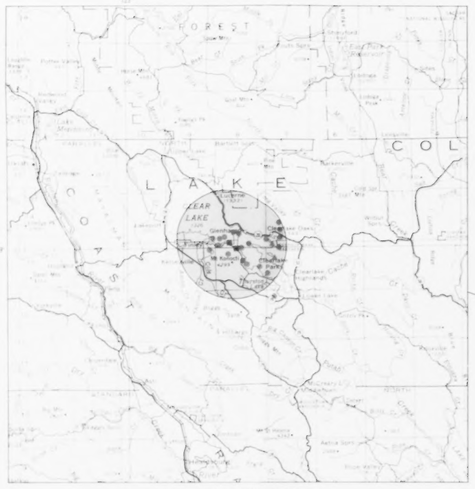
Areas subject to tephra hazards

Tephra-hazard zones are shown for vents which have erupted explosively during Holocene time and are thought to be likely sources for future explosive eruptions of fragmental material.

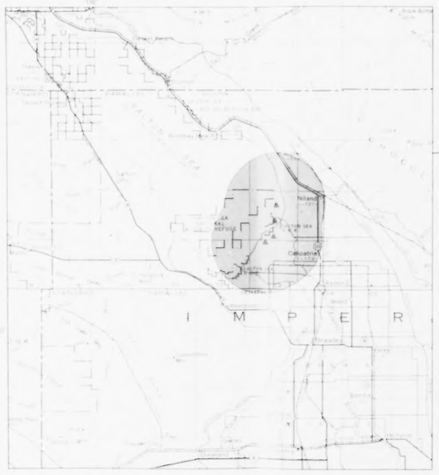
Tephra-hazard zone (locally precedented)—Areas subject to ash falls from vents considered relatively likely to erupt explosively. Extent of zone at each volcano is based on distribution, thickness, and forms of basaltic ash fall from that volcano during the last 10,000 yr.

- zone X—Area beyond flanks of volcano subject to 20 cm (8 in.) or more of compacted ash
- zone Y—Area subject to 5 cm (2 in.) or more of compacted ash

Areas subject to tephra hazards are dotted with basalt or basaltic-andesite vents. Zones are shown on maps only where a 10-km (6-mi) radius extends beyond flowage-hazard zones around mafic Holocene vents. Specific locations of future vents of this type cannot be predicted, but such eruptions will probably occur in fields of mafic vents where they have occurred in the past. Winds are not known considered in determining the shape of these zones because eruptions of this type do not usually eject material high enough to be affected by winds.



II. CLEAR LAKE AREA



VI. SALTON BUTTES AREA

INDEX MAP OF CALIFORNIA

IV. OWENS RIVER, U

HAZARDOUS VOLCANIC VENTS IN CALIFORNIA

Sources of information used to compile details about vents, eruptions and eruption products are listed below. Much of the data about the age, character, and timing of eruptions resulted from this study. Complete references can be found at end of text.

MOUNT SHASTA
Christiansen, 1985; Miller, 1978; Miller, 1980

MEDICINE LAKE HIGHLAND
Chesterman, 1955; Donnelly-Nolan, 1985; Finch, 1933; Fink and Pollard, 1983; Heath, 1959; Ives and others, 1967; Ives and others, 1964; Mertzman, 1977

LASSEN PEAK
Anderson, 1940; Crandell and others, 1978; Day and Allen, 1925; Finch, 1937; Heath, 1959; Rubin and Alexander, 1960; Williams, 1928

CLEAR LAKE AREA
Beers and others, 1976; Hearn and others, 1976; Sims and Rymer, 1975

MONO LAKE-LONG VALLEY AREA
Bailey and others, 1976; Dalrymple, 1976; Lajoie, 1968; Mankinen and others, 1986; Miller, 1982; Miller and others, 1982; Reinhart and Huber, 1965; Tadducci and others, 1968; Wood, 1983

OWENS RIVER, UBEHEBE CRATER, AND COSO AREAS
Crowe and Fisher, 1973; Duffield and others, 1980; Lanphere and others, 1975; Moore and Lanphere, 1983

AMBOY CRATER, LAVIC LAKE AREA
Dohrenwend and others, 1984

SALTON BUTTES AREA
Muffler and White, 1969; Robinson and others, 1976

V. AMBOY CRATE

SCALE 1:500,000

POTENTIAL HAZARDS FROM FUTURE VOLCANIC ERUPTIONS IN CALIFORNIA

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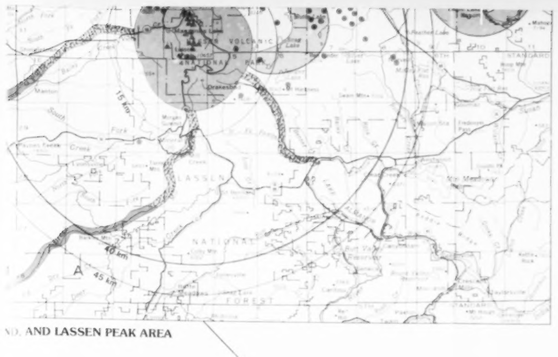
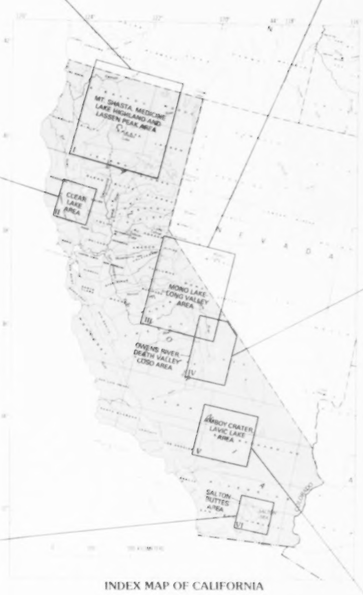


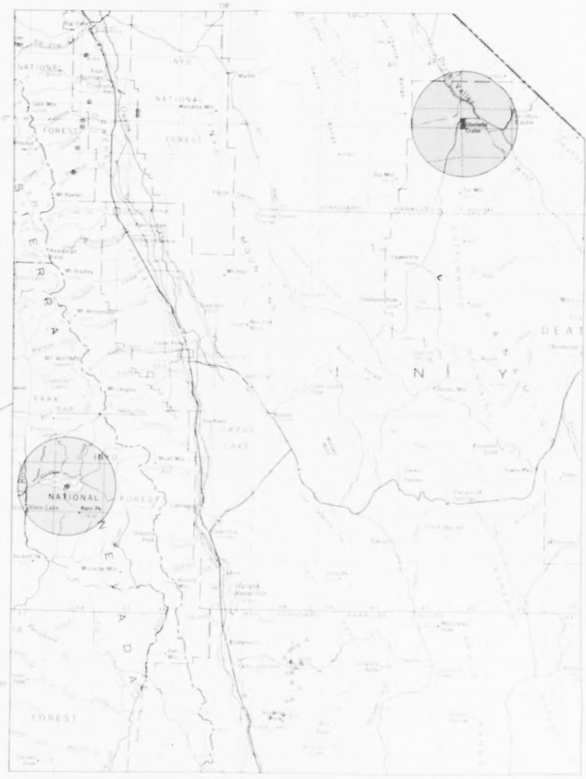
NO. AND LASSEN PEAK AREA

III. MONO LAKE-LONG VALLEY AREA

AREA


MT. SHASTA, MEDICINE LAKE HIGHLAND, AND LASSEN PEAK AREA
CLEAR LAKE AREA
MONO LAKE-LONG VALLEY AREA
OWENS RIVER-DEATH VALLEY-LONG AREA
AMBOY CRATER, LAVIC LAKE AREA
SALTON BUTTES AREA

INDEX MAP OF CALIFORNIA



IV. OWENS RIVER, UBEHEBE CRATER, COSO AREAS

REA

HAZARDOUS VOLCANIC VENTS IN CALIFORNIA

Sources of information used to compile details about vents, eruptions, and eruption products are listed below. Much of the data about the age, character, and timing of eruptions resulted from this study. Complete references can be found at end of text.

MOUNT SHASTA
Christiansen, 1985; Miller, 1978; Miller, 1980

MEDICINE LAKE HIGHLAND
Chesterman, 1955; Donnelly-Nolan, 1985; Finch, 1933; Fink and Pollard, 1983; Heath, 1959; Ives and others, 1967; Ives and others, 1964; Mertzman, 1977

LASSEN PEAK
Anderson, 1940; Crandell and others, 1978; Day and Allen, 1925; Finch, 1937; Heath, 1959; Rubin and Alexander, 1960; Williams, 1929

CLEAR LAKE AREA
Berry and others, 1976; Hearn and others, 1976; Sims and Rymer, 1975

MONO LAKE-LONG VALLEY AREA
Bailey and others, 1976; Dalrymple, 1976; Lajoie, 1968; Mankinen and others, 1986; Miller, 1982; Miller and others, 1982; Reinhart and Huber, 1965; Tadducci and others, 1968; Wood, 1983

OWENS RIVER, UBEHEBE CRATER, AND COSO AREAS
Crowe and Fisher, 1973; Duffield and others, 1980; Lanphere and others, 1975; Moore and Lanphere, 1983

AMBOY CRATER, LAVIC LAKE AREA
Dohrenwend and others, 1984

SALTON BUTTES AREA
Muffler and White, 1969; Robinson and others, 1976

V. AMBOY CRATER, LAVIC LAKE AREA

SCALE 1:500,000

POTENTIAL HAZARDS FROM FUTURE VOLCANIC ERUPTIONS IN CALIFORNIA

1847

Table 1. Potential hazards from future eruptions in California

	FLOWAGE PHENOMENA								ERUPTION OF TEPHRA	EMISSION OF VOLCANIC GASES
	Debris avalanches	Pyroclastic flows	Lateral blasts	Pyroclastic surges	Lava flows	Lava domes	Debris flows	Floods		
ORIGIN AND CHARACTERISTICS	Result from failure of volcanic edifice. Move downslope away from volcano at high speed. Distribution is partly controlled by topography.	Can be caused by direct eruption of fragments of molten or hot solid rock or by explosion or collapse of a lava dome or flow. Commonly occur suddenly and move away from volcano at tens of km to more than 100 km per hour. Distribution is mostly controlled by topography.	Result from explosive ejection of rock fragments with or without magma and steam. Commonly occur suddenly; ejected debris moves away from vent at hundreds of km per hour. Distribution controlled by direction of blast, only slightly influenced by topography.	Result from explosive magmatic or phreatic expulsion of rock fragments with steam or other hot gases. Pyroclastic surges commonly occur suddenly and ejected debris moves away from vent at hundreds of km per hour. Distribution controlled only slightly by topography.	Result from nonexplosive eruption of molten lava. Flows move down slope slowly, usually no faster than a person can walk. Distribution is controlled by topography.	Result from nonexplosive eruption of molten lava. Lava is erupted slowly and accumulates above the vent. Distribution limited to above and within a few km laterally from vent.	Commonly result from eruption of hot material onto snow and ice and from eruptive displacement of crater lakes. May also be derived from debris avalanches from volcano. Debris flows commonly originate suddenly and move at tens of km per hour. Distribution controlled by topography.	Origin similar to origin of debris flows. Debris flows may grade downstream to floods. Commonly move at speeds of <20 km per hour. Distribution controlled by topography.	Produced by vertical expulsion of columns of fragments and gas into the air; materials can be carried great distances by wind. Commonly is erupted suddenly, and is carried away from vent at speeds of tens of km per hour. Distribution controlled by height to which erupted and wind direction and speed.	Produced by explosive or nonexplosive emission of gases from vent; gases may be hot and commonly contain sulfur and other harmful compounds. Gases commonly are carried by wind away from vent at speeds of tens of km per hour. Distribution controlled by wind direction and speed.
EFFECTS ON LAND AND OBJECTS	Burial, destruction by impact, or dislocation.	Burning, burial, impact damage, and dislodgement.	Burning, burial, impact damage, and dislodgement.	Burning, burial, impact damage, and dislodgement.	Burial or destruction. May start fires.	Near-vent areas subject to burning, burial, or destruction; distant land and objects may be destroyed by pyroclastic flows generated by explosion or collapse of dome.	Burial, dislodgement, and impact damage.	Dislodgement, impact damage, and inundation by water.	Near-vent areas subject to burial, loading, and infiltration by abrasive rock particles. Blanketing and infiltration effects can reach hundreds of km downwind.	Structures, equipment, people, animals, and vegetation can be damaged or destroyed by corrosive gases. Odor, "haze" and mild effects can extend hundreds of km downwind.
DEGREE OF RISK IN AFFECTED AREA	Extreme for both people and property near and downslope from source. Risk decreases gradually away from volcano.	Extreme for both people and property near erupting volcano. Risk to people high because of possible sudden origin and high speeds. Risk decreases gradually with distance from vent, and more abruptly with increasing height above valley floor.	Extreme for both people and property within 30 km of vent because of sudden onset and very high speeds. Risk decreases gradually away from vent but does not depend on topographic position.	High for both people and property because of sudden onset and high speed. Risk decreases gradually away from from vent.	Low for people; high for property.	Low for people; high for property. Risk is greatest at vent and decreases rapidly away from the vent. Risk from dome-related pyroclastic flows may extend 15 km beyond vent.	Moderate to high for both people and property near erupting volcano. Risk decreases gradually with distance from vent and abruptly with with increasing height above valley floor.	Low to moderate for both people and property. Risk decreases gradually downvalley and abruptly with increasing height above valley floor.	Moderate to people and property near volcano. Risk decreases rapidly upwind and gradually downwind from vent.	Low to people and property. Risk decreases rapidly upwind and gradually downwind from vent.
LOCATION OF HAZARD	Areas downslope and downvalley from volcano. Large-volume debris avalanches, which occur only at large steep-sided volcanoes, may extend as far as 45 km.	Beyond volcano flanks, effects may extend as far as 40 km downslope and 65 km downvalley. Areas adjacent to pyroclastic flows may be affected for a distance of several km by clouds of hot ash.	Beyond volcano in a sector as wide as 180° that extends as far as 30 km from volcano. Ridge crests and valley floors may be affected about equally.	Areas within a distance of 10 km of vent. Topographically high and low areas may be affected about equally.	Restricted to areas downslope from vents, and most will reach distances <10 km. Flows occur repeatedly at central-vent volcanoes, but successive eruptions may affect different flanks. Elsewhere, flows occur at widely scattered sites, mostly within volcanic fields.	At vent and within a few km of vent. Pyroclastic flows resulting from collapse or explosion may extend downslope or downvalley as far as 15 km.	Beyond volcano flanks, effects mostly confined to floors of valleys and basins that head on volcanoes. Large, snow-covered volcanoes are principal sources. May extend tens to hundreds of km from source volcanoes.	Confined primarily to floors of valleys and basins that head on large, snow-covered volcanoes. May extend for hundreds of km downstream.	Areas near and downwind from volcanoes are susceptible. Zones X and Y (see text and explanation) surround volcanoes that have been explosively active during the last 10,000 yr.	All areas at and within a few hundred km downwind from erupting volcanoes or other gas emitting vents.
PREDICTABILITY OF LOCATION OF ENDANGERED AREAS	Relatively predictable, because most originate at large, steep-sided volcanoes and are restricted to flanks of volcanoes, immediately adjacent areas, and valleys leading from them.	Relatively predictable, because most originate at central-vent volcanoes or areas of past silicic volcanism. Pyroclastic flows are restricted to flanks of volcanoes and valleys leading from them.	Difficult to predict; may be predictable after eruption precursors begin. Deformation of volcano may indicate sector away from volcano most likely to be affected.	Difficult to predict. May occur wherever magma or hot rock reaches the water table or standing water, whether or not magma has erupted there before.	Relatively predictable near large central-vent volcanoes. Only general locations predictable within volcanic fields.	Relatively predictable because most originate in areas of past silicic volcanism and are restricted to small areas near vent.	Relatively predictable, because most originate at snow-covered volcanoes and are restricted to flanks of volcanoes and valleys leading from them.	Relatively predictable, because most originate at snow-covered volcanoes and are restricted to valley bottoms leading from them.	Moderately predictable. Voluminous tephra originates mostly at silicic volcanoes; its distribution depends mostly on winds. Tephra can be carried in any direction; probability of dispersal in various directions can be judged from wind records.	Moderately predictable, because most serious effects occur at or near erupting volcanoes. Distribution of gases away from vent depends on wind directions.
SIZE OF AREA AFFECTED BY SINGE EVENT	May cover areas ranging from a few tens to several hundred square km.	Generally cover a few square km to a few hundred square km.	Generally cover a few tens of square km to as much as 600 km^2.	Generally cover a few square km to several tens of square km.	Most cover no more than a few square km. Relatively large and rare flows probably would cover no more than a few tens of square km.	Generally cover no more than a few square km. Domes that spread farther considered to be lava flows.	Generally cover a few square km to a few hundred square km.	May affect a few square km to a few hundred square km.	An eruption with a volume of several km^3 could affect tens of thousands of square km and spread tephra over many states. An eruption of moderate volume (0.1-1.0 km^3) could affect many thousands of square km.	May affect several hundred square km. However, severe effects will be limited to a smaller area near the volcano.

Table 2. Summary of Holocene eruptive activity and probable greatest hazards from future eruptions at volcanic centers in California
[~, about; >, more than; ≥, greater than or equal to; <, less than]

	Volcanic center (reference)	Recognized products of recent eruptions of major volcanic centers[1,2]: Lava flows and cinder cones	Domes	Tephra	Pyroclastic flows	Blasts and pyroclastic surges	Debris avalanches and debris flows	Most recent eruption (reference)	Most probable future[3] potential hazard
	Mount Shasta (10,000 yr). (Christiansen, 1985; Miller, 1978; Miller, 1980)	Many lava flows and 1 cinder cone erupted at several vents between 10,000 and ~2,000 yr ago.	Two domes formed between ~10,000 and 9,000 yr ago; one formed during the last ~2,000 yr.	Two tephra eruptions of small volume between ~10,000 and 9,000 yr ago; probable volume 0.001-0.1 km^3.	Many pyroclastic flows down all sides of the volcano; some traveled ≥20 km from summit.	None recognized	Many debris flows down all sides of the volcano; many reached >30 km from volcano; one reached more than 40 km from volcano.	Small pyroclastic flows, associated ash clouds and debris flows ~200 ¹⁴C yrs ago. (Miller, 1980)	Formation of large pyroclastic flows and debris flows.
MEDICINE LAKE HIGHLAND REGION	Rhyolite center (1,500 yr). (Chesterman, 1955; Fink and Pollard, 1983; Heiken, 1978; Ives and others, 1964, 1967; Mertzman, 1977)	At least four lava flows during the last 1,500 yr.	Many small silicic domes formed within the last 1,500 yr.	Two tephra eruptions of small volume during the last 1,500 yr; one slightly older; probable volume 0.05-0.1 km^3.	None recognized	None recognized	None recognized	Lava flows erupted within the last 1,500 yr. (Heiken, 1978)	Formation of relatively small pyroclastic flows; eruption of tephra.
	Basalt field (10,000 yr). (Finch, 1933)	At least 15 lava flows and (or) cinder cones within about the last 10,000 yr.	None recognized	Small volumes of mafic tephra erupted with cinder cones and flows.	None recognized	None recognized	None recognized	Several lava flows probably erupted during the last few hundred years. (Finch, 1933)	Formation of cinder cones, small volumes of tephra, and lava flows.
LASSEN PEAK REGION	Lassen area dacites (12,000 yr). (Clynne, 1985; Crandell, and others, 1974; Day and Allen, 1925; Heath, 1959; Rubin and Alexander, 1960)	At least one small lava flow in A.D. 1915.	At least eight silicic domes within the last 12,000 yr; four between ~12,000 and 11,000 yr; three ~1,000 yr ago; one ~350 yr ago.	Tephra eruption ~1,100 yr ago.	Two pyroclastic flows between ~12,000 and 11,000 yr ago; three pyroclastic flows ~1,100 yr ago; two pyroclastic flows ~300 yr ago.	Two small directed blasts (or pyroclastic flows) in A.D. 1915; effects extend to distance of 5 km from summit.	Dozens of debris flows were generated during eruptions at Lassen Peak dome ~11,000 yr ago; several debris avalanches ~300 yr ago; two small debris flows in A.D. 1915.	Lava flow, tephra fall, hot debris flows, and two small blasts in A.D. 1914-1917. (Clynne, 1985; Day and Allen, 1925)	Formation of pyroclastic flows, small to moderate-size debris flows.
	Basalt field (10,000 yr). (Anderson, 1940; Finch, 1937; Williams, 1928)	Eruption of >20 mafic centers producing lava flows and (or) cinder cones during the last 10,000 yr.	None recognized	Small volumes of mafic tephra erupted at many centers during Holocene time. ~40 km^2 covered with	None recognized	None recognized	None recognized	Lava flows, tephra and cinder cone erupted in A.D. 1851. (Clynne, 1985; Finch, 1937; Williams, 1928)	Formation of cinder cones, small volumes of tephra, and lava flows.

	ted to flanks of volcanoes, immediately adjacent areas, and valleys leading from them.	of past silicic volcanism. Pyroclastic flows are restricted to flanks of volcanoes and valleys leading from them.	volcano may indicate sector away from volcano most likely to be affected.	water, whether or not magma has erupted there before.	predictable within volcanic fields.	and are restricted to small areas near vent.	restricted to flanks of volcanoes and valleys leading from them.	are restricted to valley bottoms leading from them.	depends mostly on winds. Tephra can be carried in any direction; probability of dispersal in various directions can be judged from wind records.	gases away from vent depends on wind directions.
SIZE OF AREA AFFECTED BY SINGE EVENT	May cover areas ranging from a few tens to several hundred square km.	Generally cover a few square km to a few hundred square km.	Generally cover a few tens of square km to as much as 600 km^2.	Generally cover a few square km to several tens of square km.	Most cover no more than a few square km. Relatively large and rare flows probably would cover no more than a few tens of square km.	Generally cover no more than a few square km. Domes that spread farther considered to be lava flows.	Generally cover a few square km to a few hundred square km.	May affect a few square km to a few hundred square km.	An eruption with a volume of several km^3 could affect tens of thousands of square km and spread tephra over many states. An eruption of moderate volume (0.1-1.0 km^3) could affect many thousands of square km.	May affect several hundred square km. However, severe effects will be limited to a smaller area near the volcano.

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MEDICINE LAKE HIGHLAND REGION	Rhyolite center (1,500 yr). (Chesterman, 1955; Fink and Pollard, 1935; Heiken, 1978; Ives and others, 1964, 1967; Mertzman, 1977)	At least four lava flows during the last 1,500 yr.	Many small silicic domes formed within the last 1,500 yr.	Two tephra eruptions of small volume during the last 1,500 yr; one slightly older; probable volume 0.05-0.1 km^3.	None recognized	None recognized	None recognized	Lava flows erupted within the last 1,500 yr. (Heiken, 1978)	Formation of relatively small pyroclastic flows; eruption of tephra.
	Basalt field (10,000 yr). (Finch, 1933)	At least 15 lava flows and (or) cinder cones within about the last 10,000 yr.	None recognized	Small volumes of mafic tephra erupted with cinder cones and flows.	None recognized	None recognized	None recognized	Several lava flows probably erupted during the last few hundred years. (Finch, 1933)	Formation of cinder cones, small volumes of tephra, and lava flows.
LASSEN PEAK REGION	Lassen area dacites (12,000 yr). (Clynne, 1985; Crandell, and others, 1975; Day and Allen, 1925; Heath, 1959; Rubin and Alexander, 1960)	At least one small lava flow in A.D. 1915.	At least eight silicic domes within the last 12,000 yr; four between ~12,000 and 11,000 yr; three ~1,000 yr ago; one ~350 yr ago.	Tephra eruption ~1,100 yr ago.	Two pyroclastic flows between ~12,000 and 11,000 yr ago; three pyroclastic flows ~1,100 yr ago; two pyroclastic flows ~300 yr ago.	Two small directed blasts (or pyroclastic flows) in A.D. 1915; effects extend to distance of 5 km from summit.	Dozens of debris flows were generated during eruptions at Lassen Peak dome ~11,000 yr ago; several debris avalanches ~300 yr ago; two small debris flows in A.D. 1915.	Lava flow, tephra fall, hot debris flows, and two small blasts in A.D. 1914-1917. (Clynne, 1985; Day and Allen, 1925)	Formation of pyroclastic flows; small to moderate-size debris flows.
	Basalt field (10,000 yr). (Anderson, 1940; Finch, 1937; Williams, 1928)	Eruption of >20 mafic centers producing lava flows and (or) cinder cones during the last 10,000 yr.	None recognized	Small volumes of mafic tephra erupted at many centers during Holocene time. ~80 km^2 covered with ash from Cinder Cone about 400 yr ago.	None recognized	None recognized	None recognized	Lava flows, tephra and cinder cone erupted in A.D. 1851. (Clynne, 1985; Finch, 1937; Williams, 1928)	Formation of cinder cones, small volumes of tephra, and lava flows.
	Clear Lake (10,000 yr). (Berry and others, 1976; Hearn and others, 1976; Sims and Rymer, 1975)	None recognized	None recognized	Numerous mafic tephras were erupted during phreatomagmatic eruptions as recently as ~10,000 yr ago.	None recognized	Numerous phreatic eruptions, hydromagmatic explosions, and base-surge events.	None recognized	Mafic tephra from phreatomagmatic eruption ~10,000 yr ago. (Sims and Rymer, 1975)	Phreatic and phreatomagmatic explosions, base surges, and small-volume tephra eruptions.
MONO LAKE-LONG VALLEY AREA	Silicic vents (10,000 yr). (Bailey and others, 1976; Dalrymple, 1967; Mankinen and others, 1986; Miller, 1985; Miller and others, 1982; Reinhart and Huber, 1965; Tadduci and others, 1968; Wood, 1983)	Many silicic lava flows erupted at numerous vents between 10,000 yr ago and ~500 yr ago; possible flows younger than 500 yr B.P.	Many silicic domes erupted at numerous vents between 10,000 yr ago and ~500 yr ago.	Many silicic tephras erupted from numerous vents; volumes ranged from <0.02 km^3 to >0.2 km^3.	Many pyroclastic flows from numerous vents. Some have flowed 10-15 km from vents.	Many phreatic, phreatomagmatic and pyroclastic surge events have occurred at numerous vents.	Small debris flows have originated at several vents.	A series of explosive magmatic and phreatic eruptions and emplacement of lava flows occurred at several vents at the Inyo volcanoes ~550 yr ago. (Miller, 1983; 1985; Miller and others, 1982; Wood, 1983)	Small- to moderate-volume silicic pyroclastic eruptions that will form pyroclastic flows and small to moderate volumes of tephra.
	Mafic vents (13,000 yr). (Bailey and others, 1976; Lajoie, 1968)	Subiacustrine mafic eruptions in Mono Lake ~13,000 yr ago; eruption of cinder cones and flows at two vents 1,200-5,000 yr ago.	None recognized	Mafic cinders erupted at two vents 1,200-~5,000 yr ago.	None recognized	None recognized	None recognized	Mafic cinder cone and lava flow eruptions at two vents, 1,200-5,000 yr ago. (Miller, this report)	Formation of cinder cones, small volumes of tephra, and lava flows; phreatic explosions.
	Amboy Crater-Lavic Lake basalt fields (~10,000 yr).	Several mafic lava flows and cinder cones from several vents during last ~10,000 yr.	None recognized	Mafic tephra erupted at several vents during past ~10,000 yr.	None recognized	None recognized	None recognized	Mafic cinder cones and lava flows of apparent early Holocene age. (Miller, this report)	Formation of cinder cones, small volumes of tephra, and lava flows; phreatic explosions.
	Salton Buttes rhyolite center (16,000 yr). (Muffler and White, 1969; Robinson and others, 1976)	At least one silicic flow associated with rhyolite dome ~16,000 yr ago.	Five silicic domes erupted from four vents ~16,000 yr ago.	Probable small-volume pyroclastic eruptions associated with dome emplacement at several vents.	None recognized but may have occurred at several vents.	Products of subaqueous pyroclastic eruptions at least one vent.	None recognized	Silicic pyroclastic and extrusive eruptions at four vents ~16,000 K/Ar yr ago. Robinson and others, 1976)	Explosive and extrusive rhyolitic eruptions; phreatic and phreatomagmatic eruptions.
	Ubehebe Crater area (~10,000 yr). (Crowe and Fisher, 1973)	None recognized	None recognized	Several mafic phreatomagmatic tephra eruptions in Holocene time.	None recognized	Base-surge and phreatomagmatic tephra deposits associated with ~13 maar-crater eruptions.	None recognized	Formation of maar craters and deposition of phreatomagmatic tephra and base-surge deposits in early Holocene time. (Crowe and Fisher, 1973)	Phreatomagmatic eruptions associated with base surges and small volumes of tephra.
	Golden Trout Creek volcanic field (~10,000 yr). (Moore and Lanphere, 1983)	One mafic cinder cone and lava flow ~10,000-5,000 yr ago.	None recognized	Mafic cinders erupted at one vent ~10,000-5,000 yr ago.	None recognized	None recognized	None recognized	Mafic cinder cone and lava flow ~10,000-5,000 yr ago. (Moore and Lanphere, 1983)	Formation of cinder cones, small volumes of tephra and lava flows.

[1]Time interval evaluated shown in parentheses for each volcano.

[2]Much of these data resulted from this study; other references are cited.

[3]Based on consideration of size, frequency, and severity of event.